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Development of Advanced Spherical Torus Plasmas in NSTX

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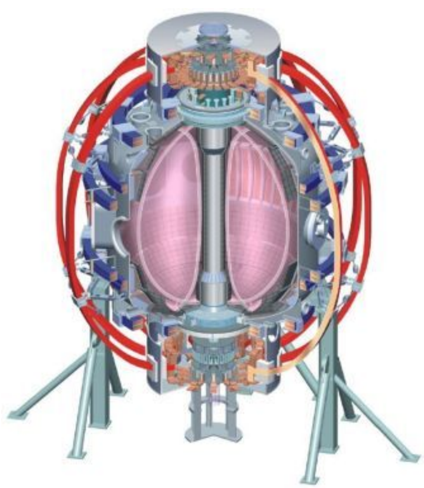
S. A. Sabbagh, ***Columbia University***
H. Yuh, ***Nova Photonics***
and the NSTX Research Team

EPS Conference on Plasma Physics, Dublin, 2010



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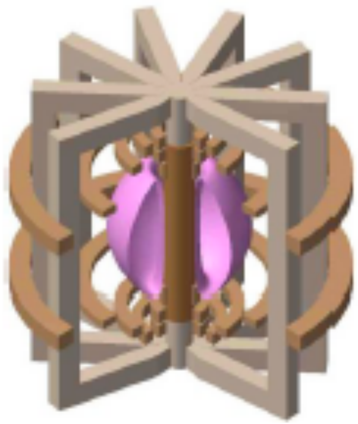
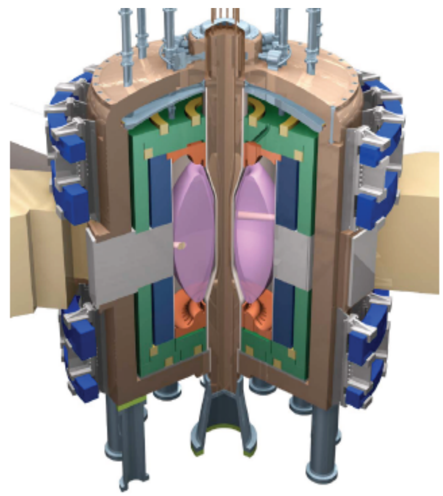
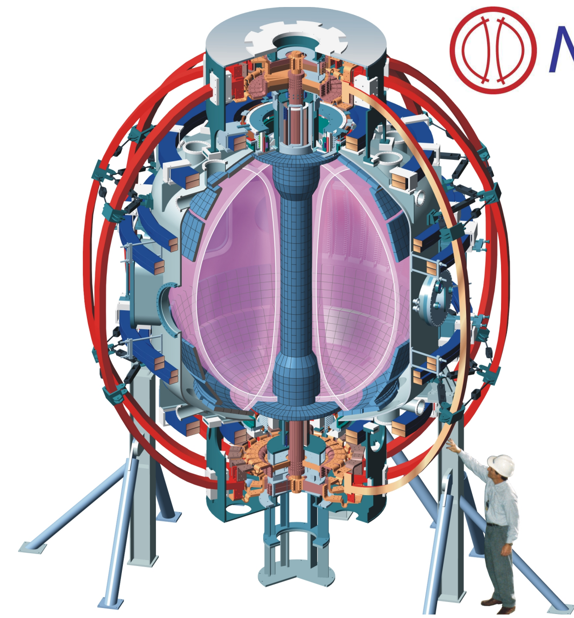
NSTX Scenario Development Research Formulated to Support the Needs of Next Step STs



ST-based Plasma Material Interface (PMI) Science Facility



ST-based Fusion Nuclear Science Facility



These designs assume steady state operation with:

- ***Confinement at or exceeding standard H-mode scaling***
- ***High-κ and high-β***
- ***Large bootstrap fractions (>50%)***
- ***Substantial neutral beam current drive***

Aspect ratio A	1.27 – 1.6
Toroidal Field B_{T0}	0.35 – 0.55 T
Plasma Current I_p	≤1.4 MA
NBI (<100kV)	7 MW

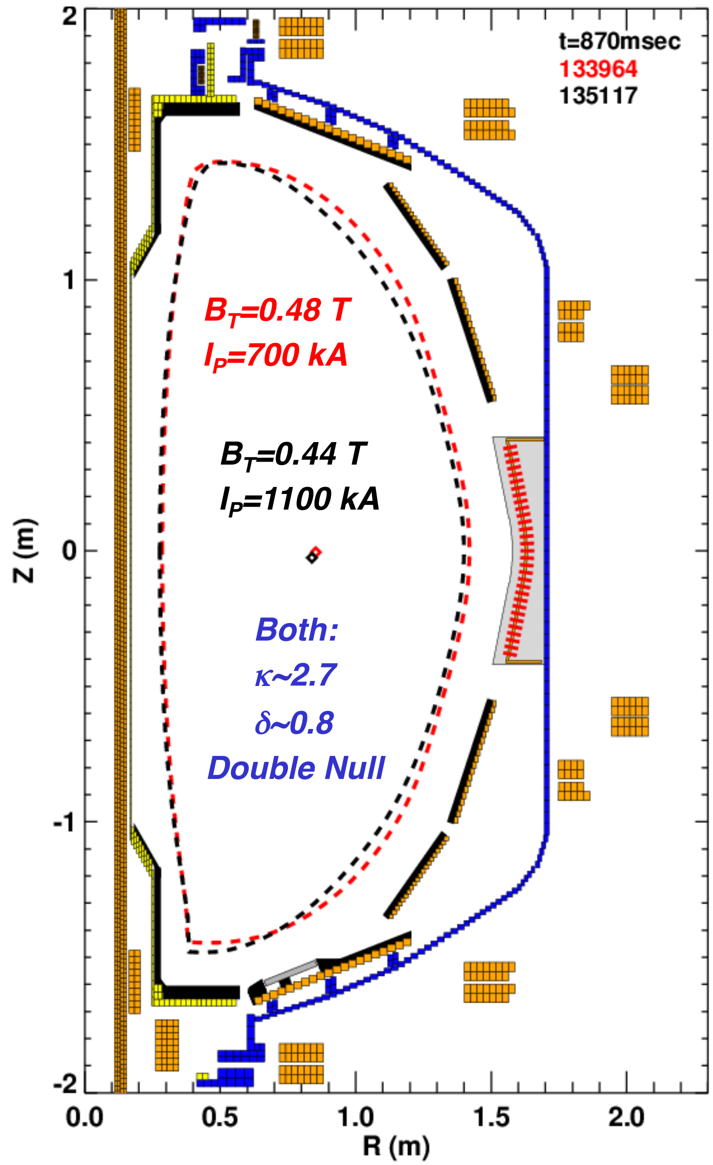
Lithium conditioning of PFCs via a dual evaporator system

Midplane radial field coils for n=1 & 3 field application

Overview: Results and Tools

- Development of long pulse high-κ and β discharge scenarios
  - Overview
  - Current profile analysis
  - Transport
  - Global MHD characteristics
- Emphasis on the tools that facilitate these scenarios.
  - Strong axisymmetric shaping
  - n=1 mode control and n=3 error field correction
  - Lithium conditioning of the PFCs

Recent Scenario Development Has Focused on Long-Pulse Development With Strong Shaping and High-β

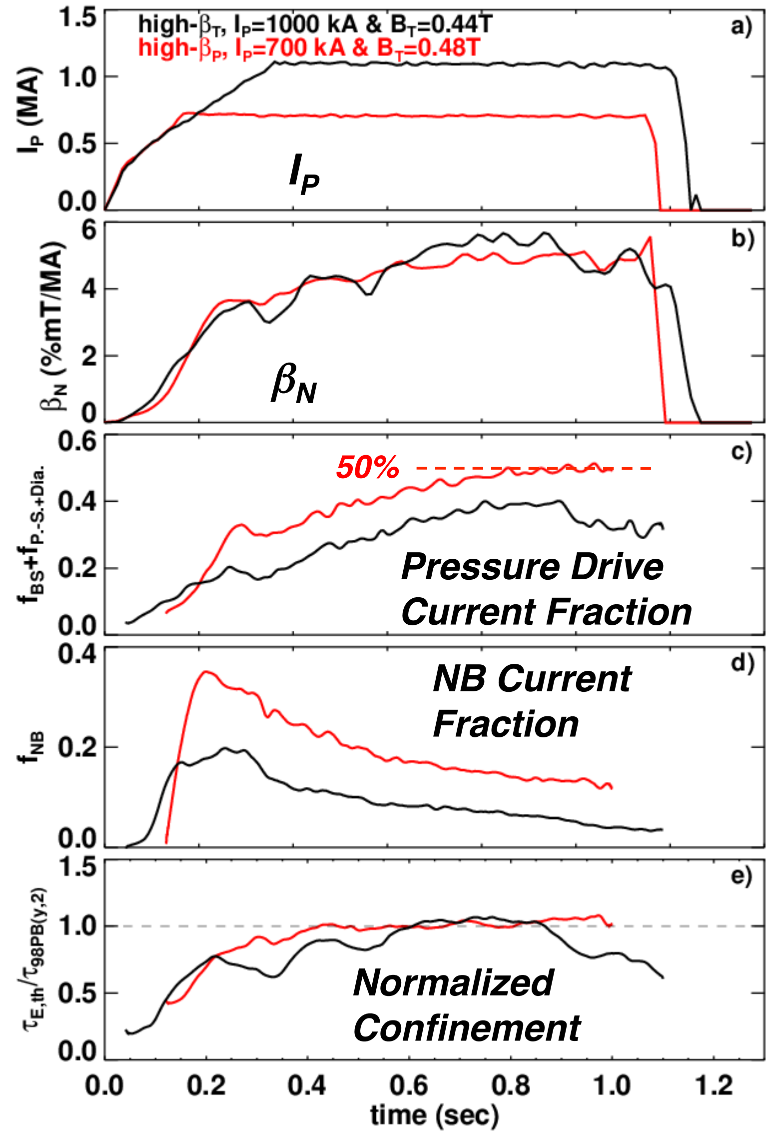


133964

Largest possible non-inductive fraction, high q_{95}.

135117

Sustained high β_T, low q_{95}.



Current Profile Can Be Reconstructed with Classical NBCD, Bootstrap Current, and Inductive Current

Current Profile Reconstructed from…

Pressure-Driven Currents: *Bootstrap, Pfirsch-Schlueter+Diamagnetic*

Inductive current: *time derivatives of reconstructed equilibria + neoclassical resistivity*

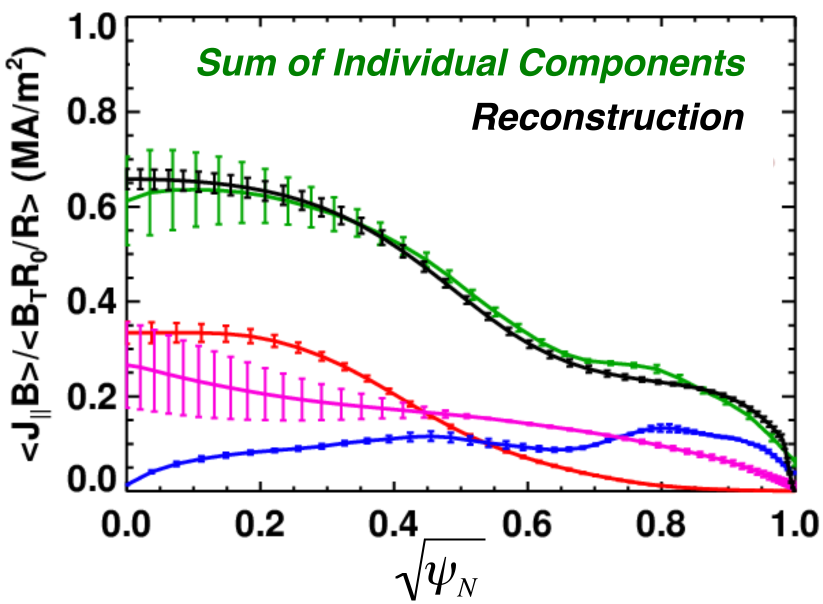
Neutral Beam Current Drive *from NUBEAM, with classical beam physics*

Compare to…

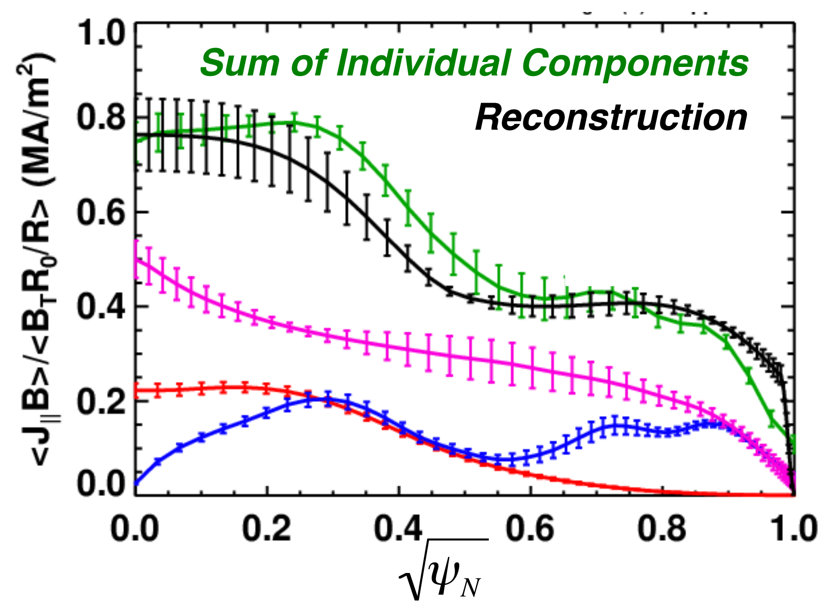
Reconstructions *constrained by MSE and T_e isotherm constraint*

Choose time with no EP MHD or low-frequency kink/tearing

High-β_P shot with highest non-inductive fraction, 700 kA

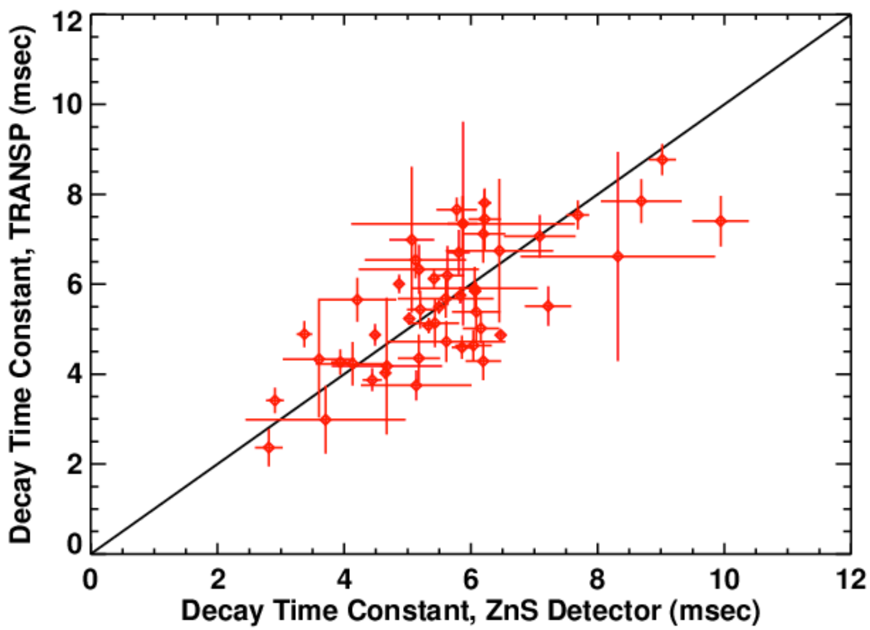


β_T=25% discharge @ 1100 kA



Use TRANSP Analysis to Show the Present Limits of Non-Inductive Current Fractions in NSTX

- Verified the match between
  - TRANSP and measured neutron rates
  - TRANSP and EFIT stored energy
- Examined the neutron emission decay time constant after beam turn-off
  - Measured and simulated decay time constants are in agreement



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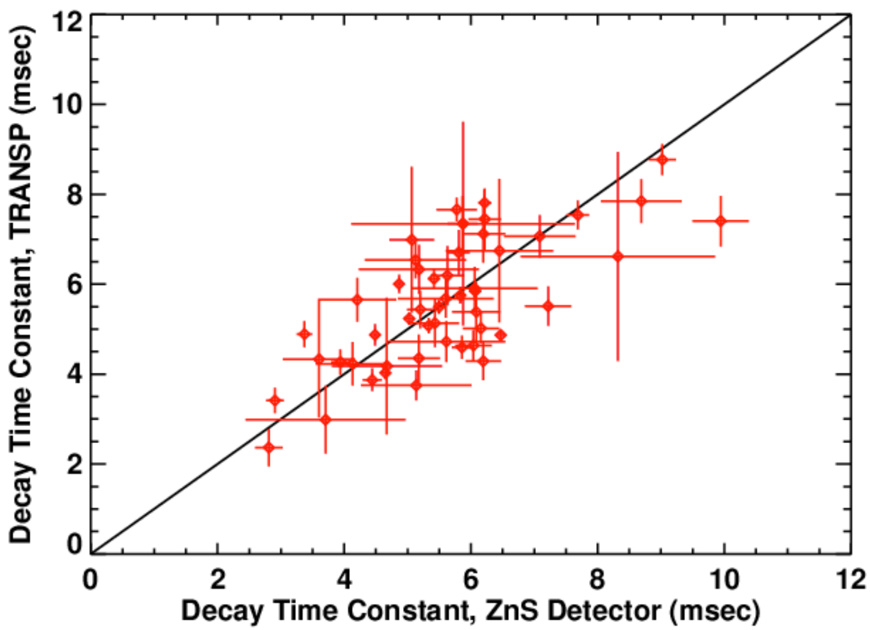
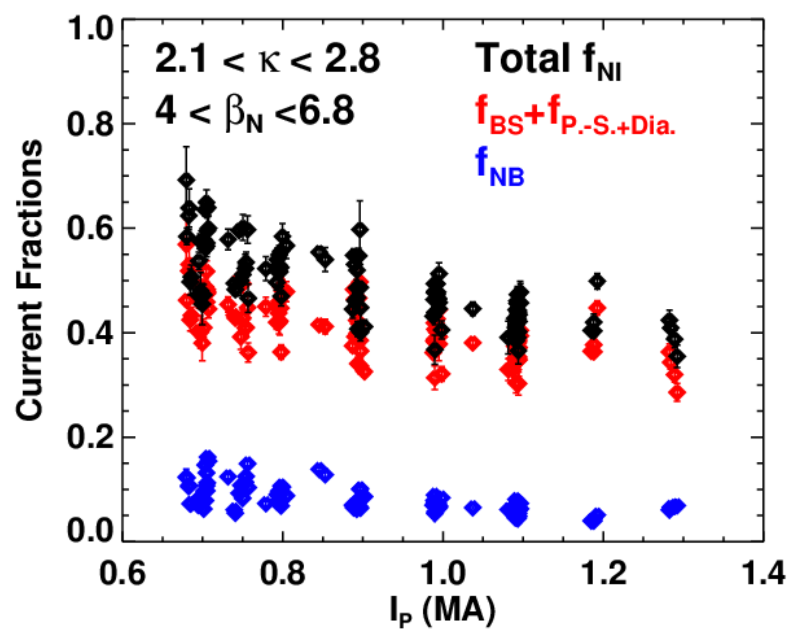
- Non-inductive fractions of 65-70% achieved at lower values of plasma current
- Further reductions in I_P prohibited by the prompt loss of fast ions
- TRANSP simulations of high β_P shot: increasing the temperatures by 50% yields f_{NI}=1

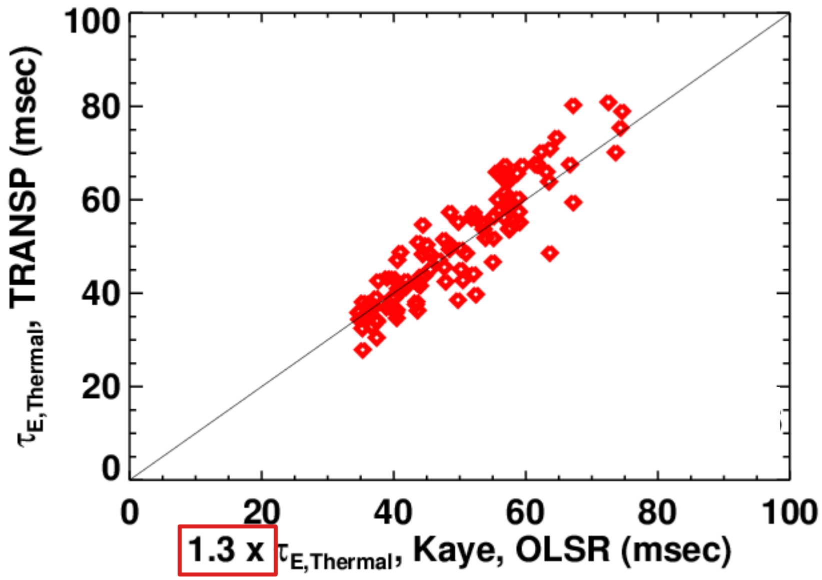




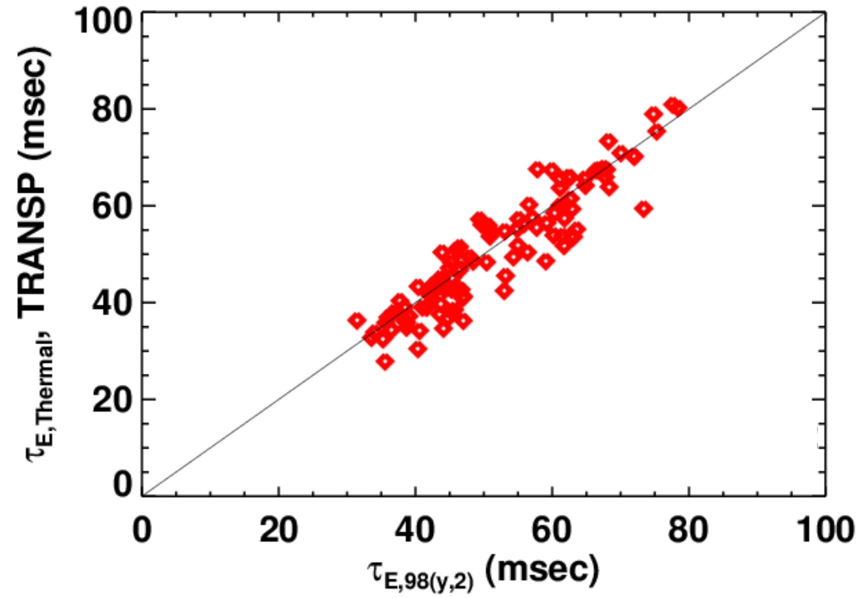
Lithium-Conditioned High-β Discharges in NSTX Have Good Confinement

- Consider > 75 msec averaging windows, at least one current diffusion time into the I_P flat-top, at high-κ and δ, in lithium conditioned discharges
  - Criterion excludes many high-confinement discharges

$$\tau_{E,th,Kaye,OLSR} \propto I_P^{0.57} B_T^{1.} n_e^{0.44} P_{abs}^{-0.73}$$



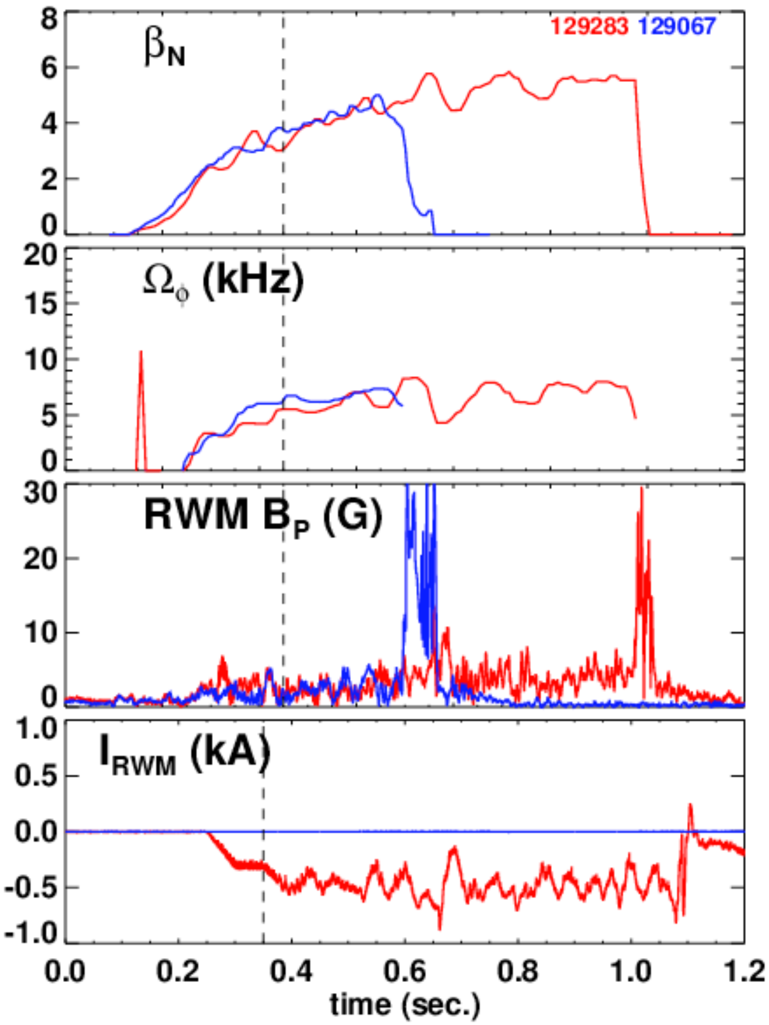
$$\tau_{E,th,ITER-98} \propto I_P^{0.93} B_T^{0.15} n_e^{0.41} P_{abs}^{-0.69} \kappa^{0.8}$$



- Confinement exceeds previous low-A scaling by 30%.
  - Lithium conditioning, strong shaping, higher β_N and longer-pulse duration.
- Working to revise ST-scalings for τ_E in this class of discharge.

NSTX Uses Active n=1 Mode Control to Access High β_N Regimes

Comparison with & without n=1 control:
- ***Dynamic Error Field Correction***
- ***Fast RWM feedback.***



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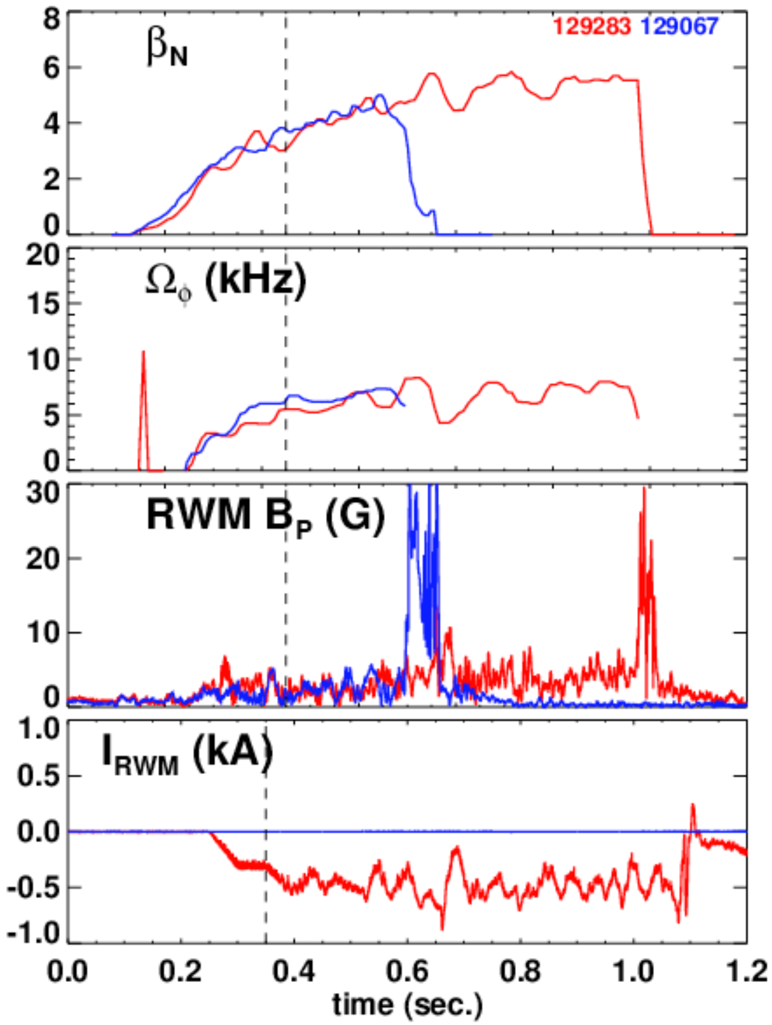

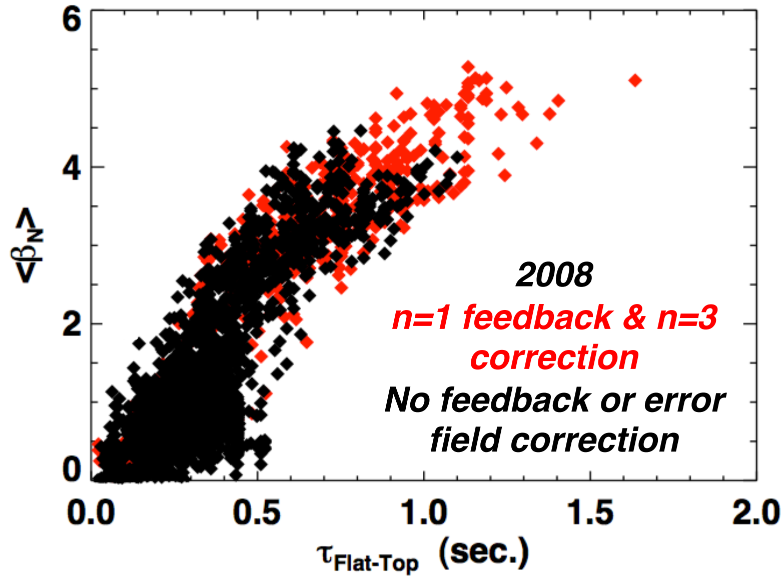

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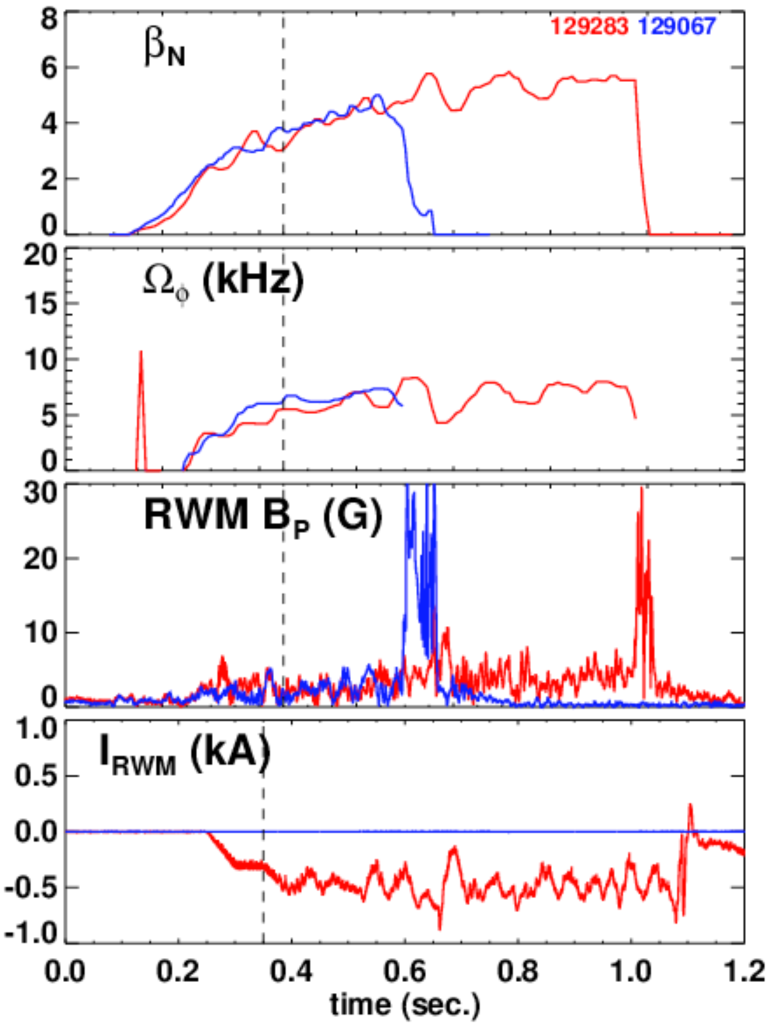
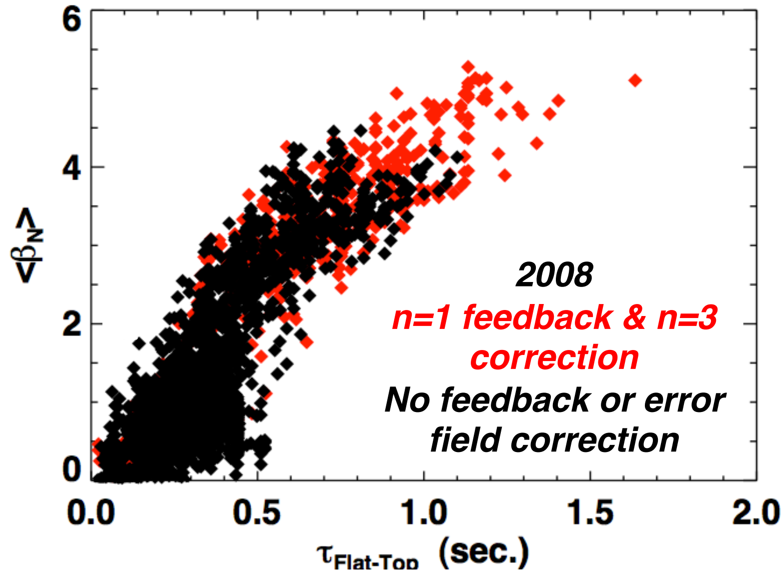
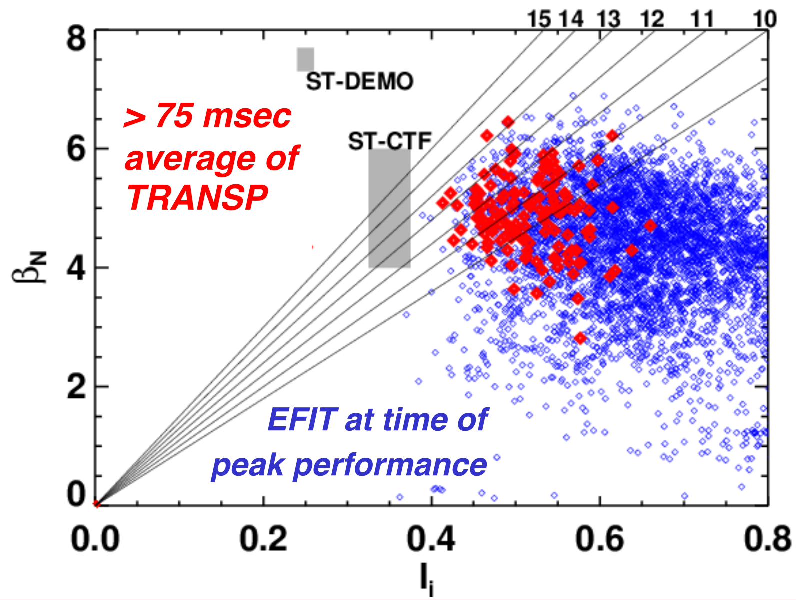
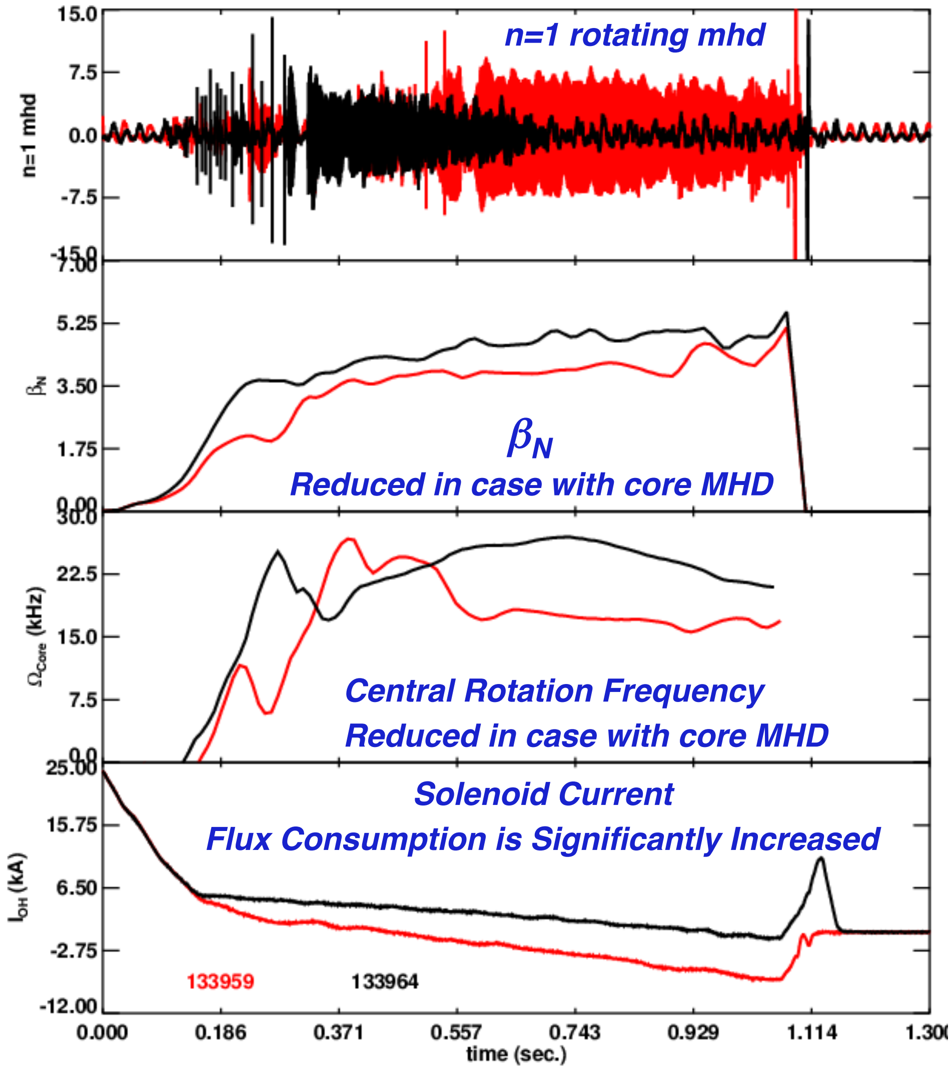






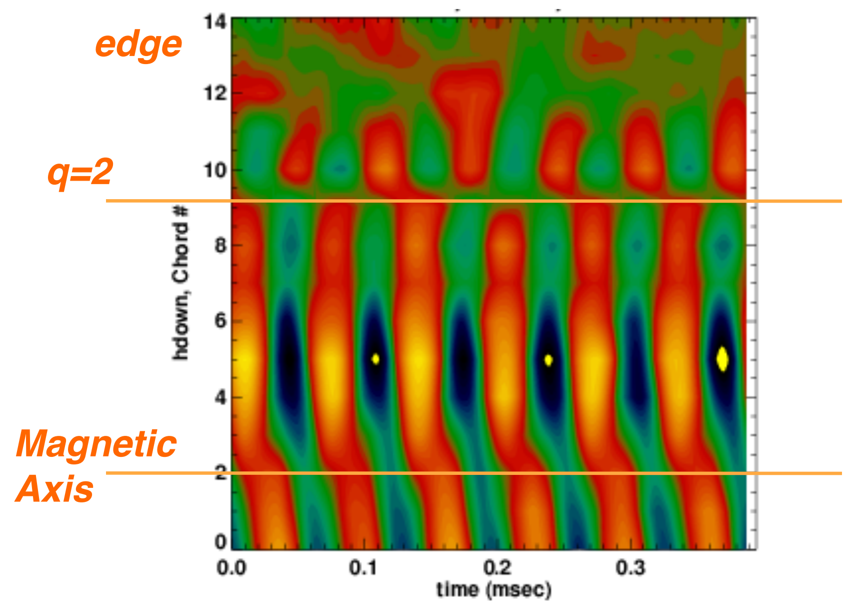
Rotating Core n=1 Instabilities Limit Performance in Many of These Discharges



Energetic particle mode triggers rotating n=1 MHD

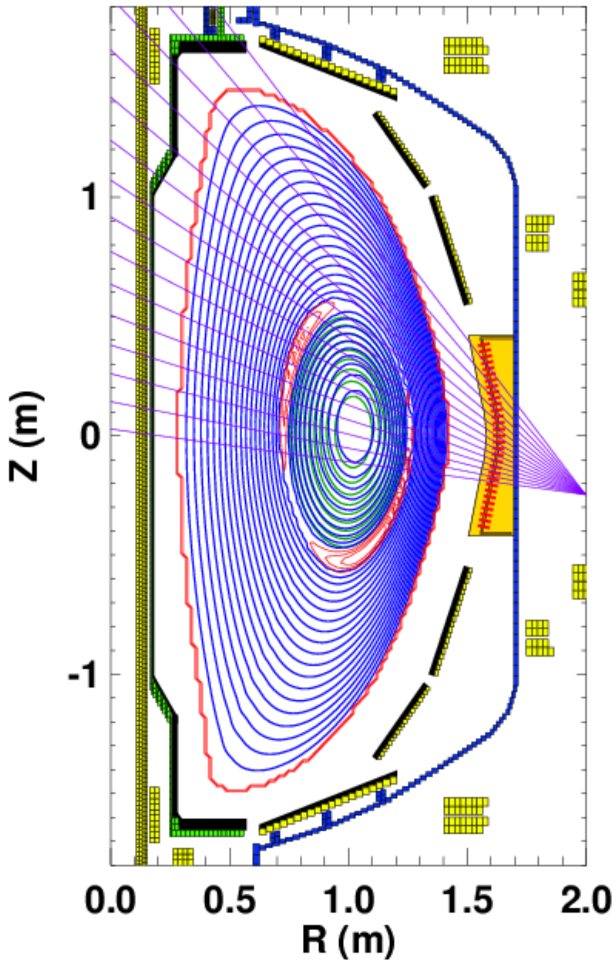
- *Reduced core rotation*
- *Reduced stored energy*
- *Increased flux consumption*
- *Mode locking and disruption*

Soft X-ray emission shows multiple inversion layers



Eigenfunction Analysis Shows m/n = 1/1+2/1 Modes Are Present in these Cases

- ***Analytic model for a m/n=2/1 magnetic island + 1/1 core kink.***
- ***"Calibrate" the island width against flat region in Thomson scattering T_e profile.***



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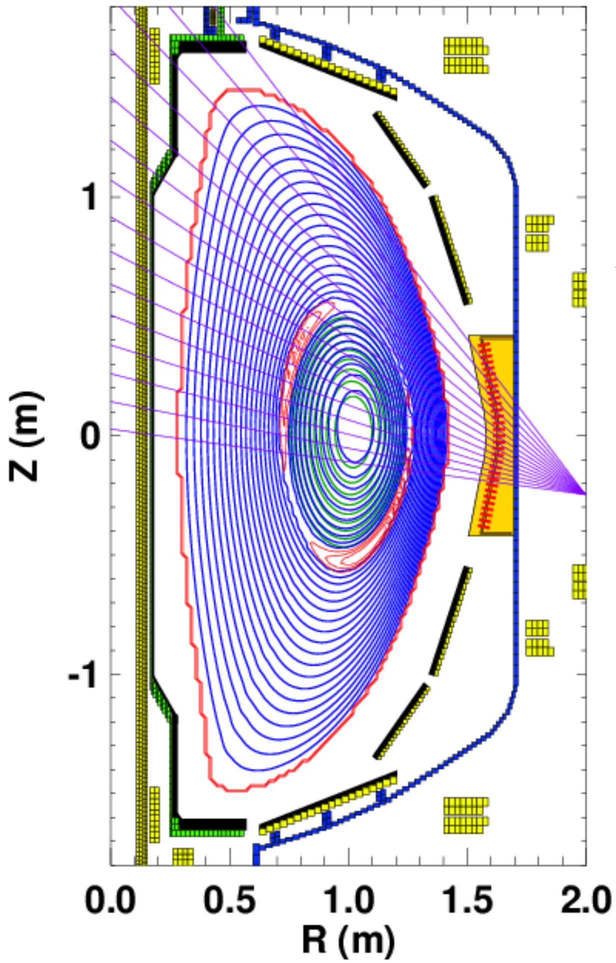
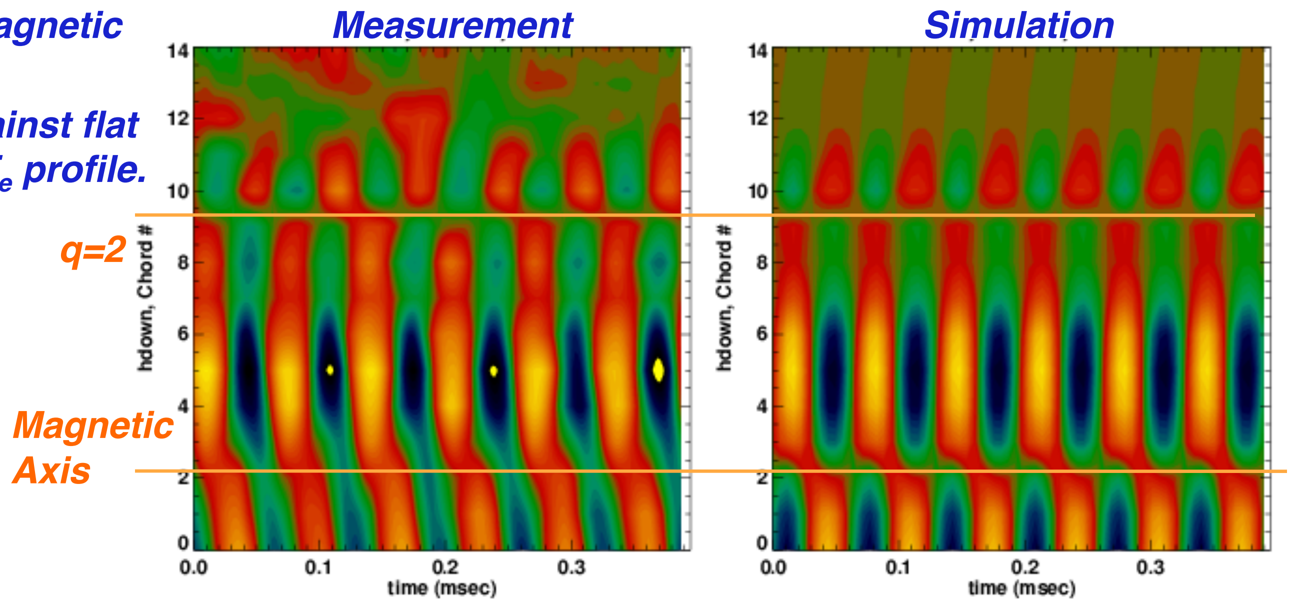


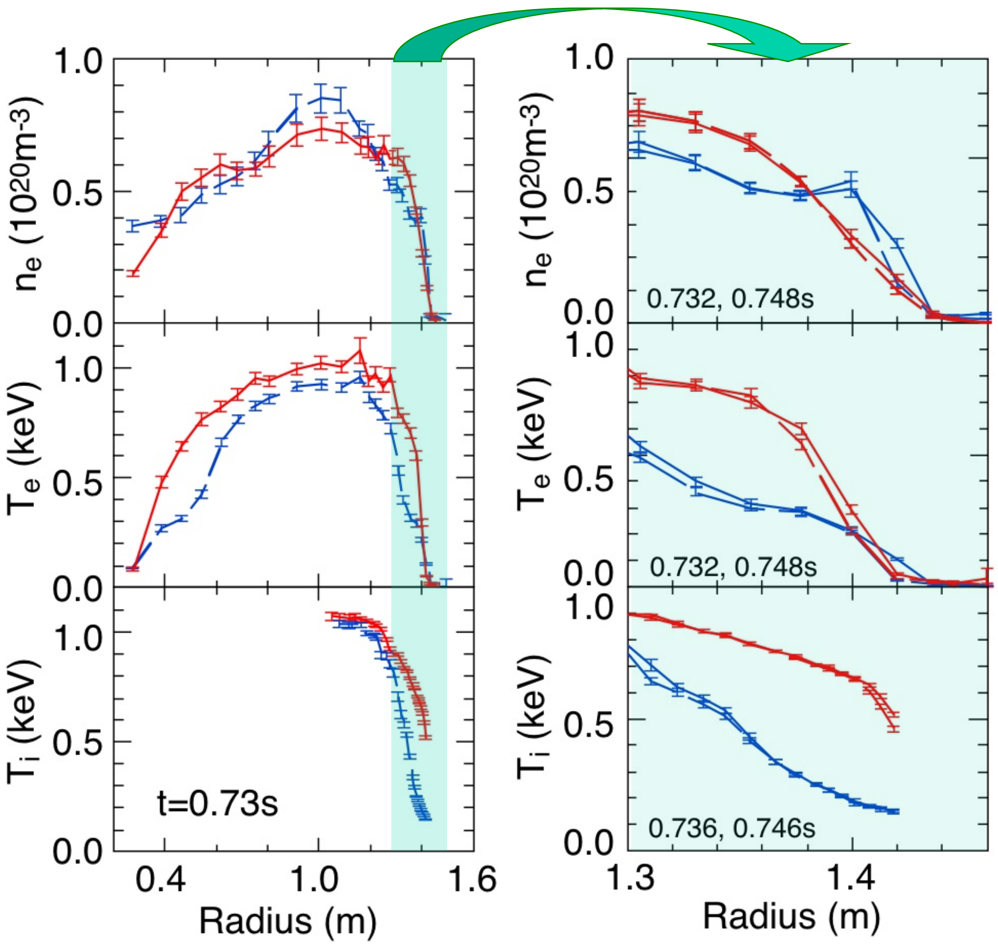


- *Can be restabilized as β is reduced.*
  - *Characteristic of an NTM*
- *Rotating MHD generally avoidable at lower normalized current*
  - *q_{min}>1.2 and ELM free with lithium PFC conditioning*
- *At higher normalized current:*
  - *too much input power -> RWM*
  - *too little power -> core kink/tearing*
- *Emphasizes the future importance of simultaneous current profile, n=1 mode, and β control.*

Lithium Wall Conditioning Modifies Kinetic Profiles, Leads to Broad Pressure Profiles Favorable For Stability

1: Profiles are modified by lithium conditioning of PFCs

No lithium (129239); **260mg lithium** (129245)



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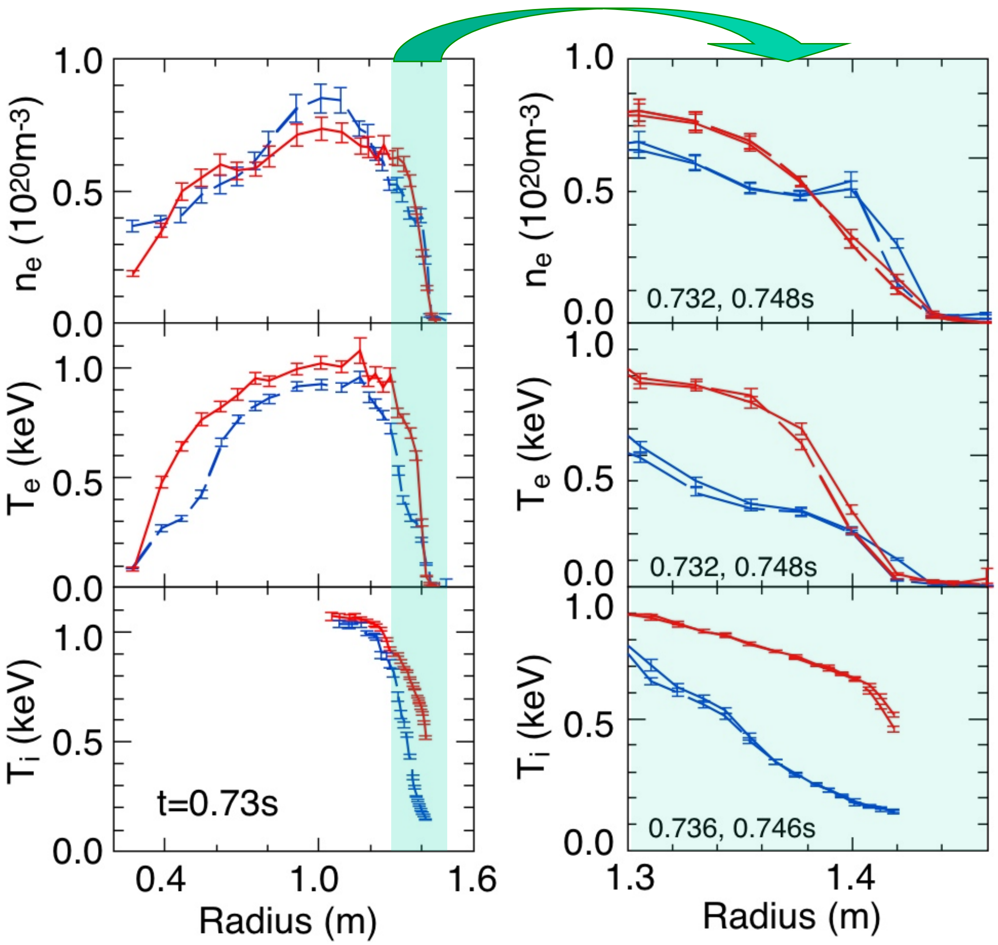
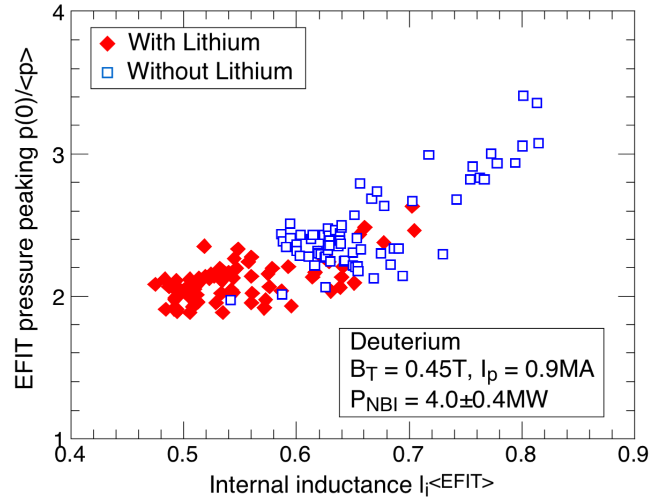


2: Pressure peaking is reduced



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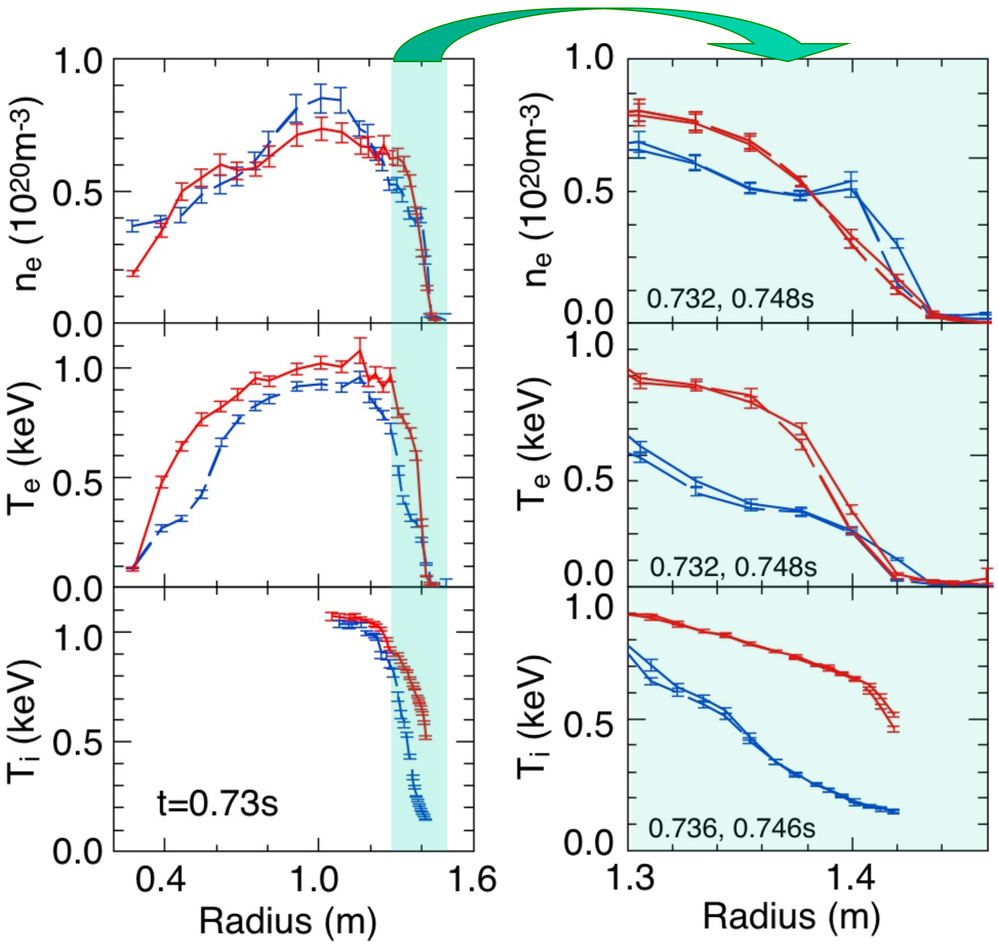

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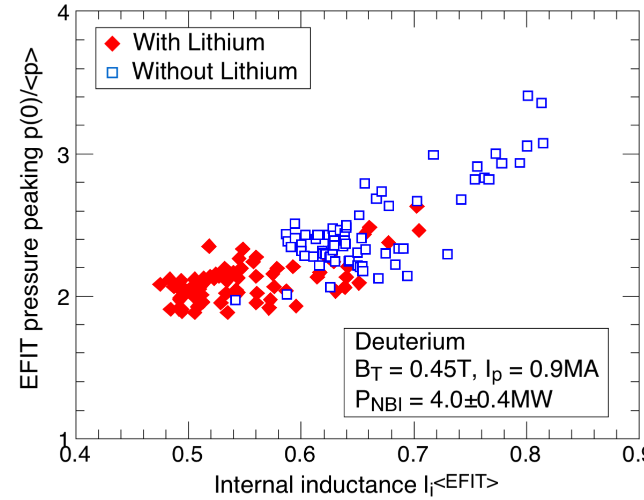
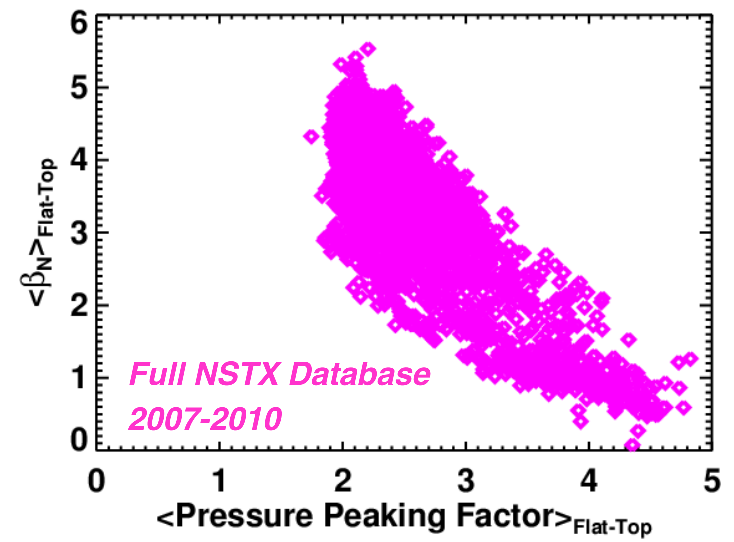


3: Global stability limit is increased

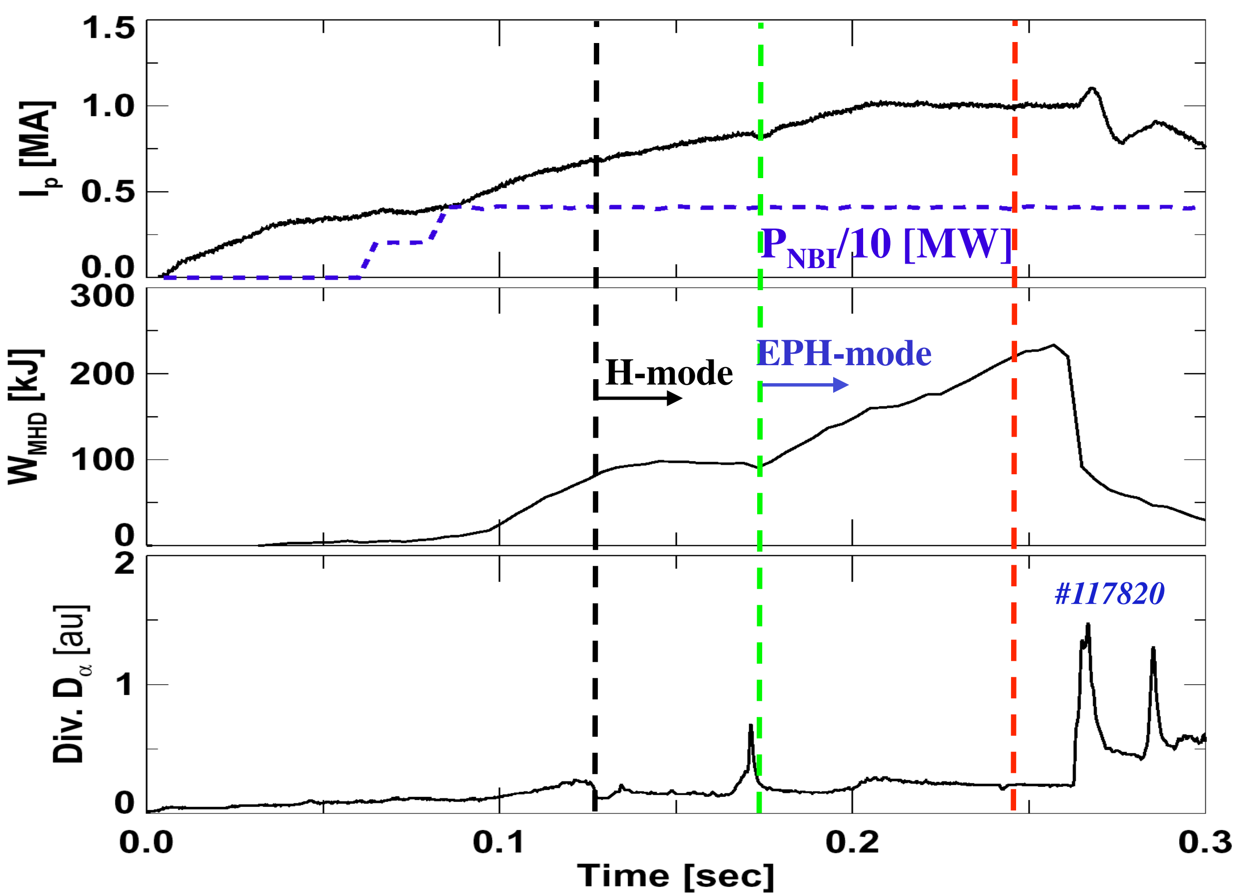


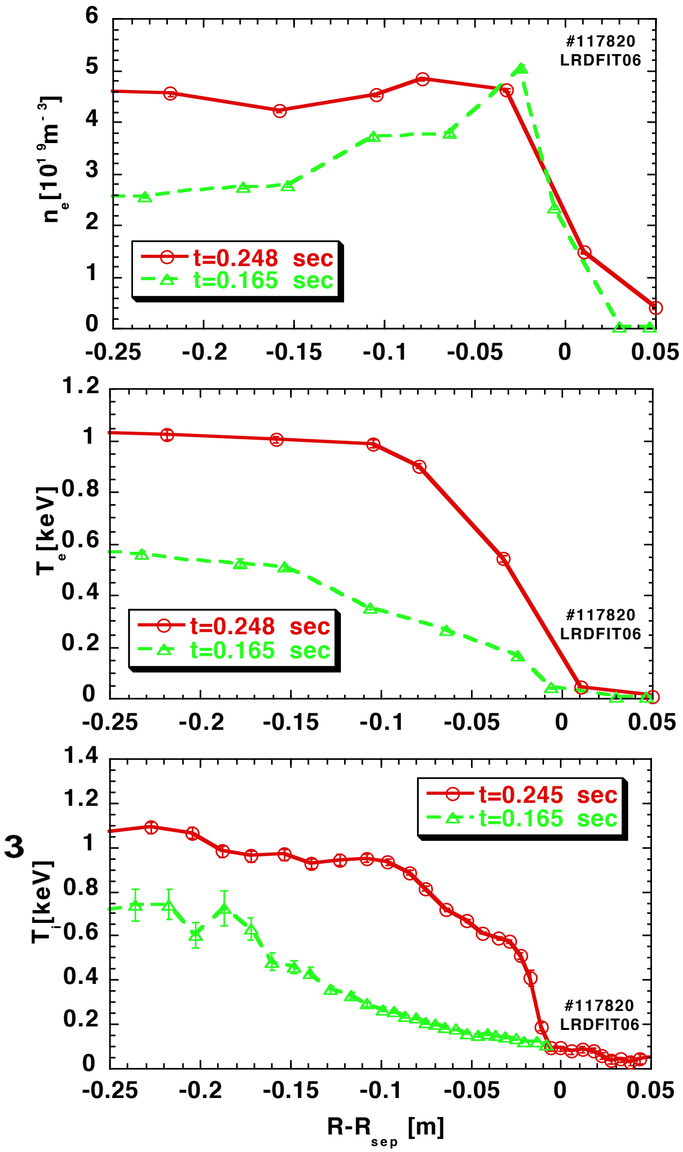
Conclusions

- High-performance plasmas in NSTX are facilitated by:
  - Strong axisymmetric shaping
  - n=1 feedback and error field correction
  - Lithium conditioning of the PFCs
- Scenarios have simultaneously demonstrated:
  - Sustained H-mode confinement comparable to good discharges in conventional aspect ratio devices
  - High-β_N, low-l_i operation in regimes of relevance to next-step devices
  - Non-inductive fractions of 65-70%

Backup

Transition to an Enhanced Pedestal H-mode enables lower pedestal $\nu_{e,ped}{}^{*} \sim 0.1$ in NSTX

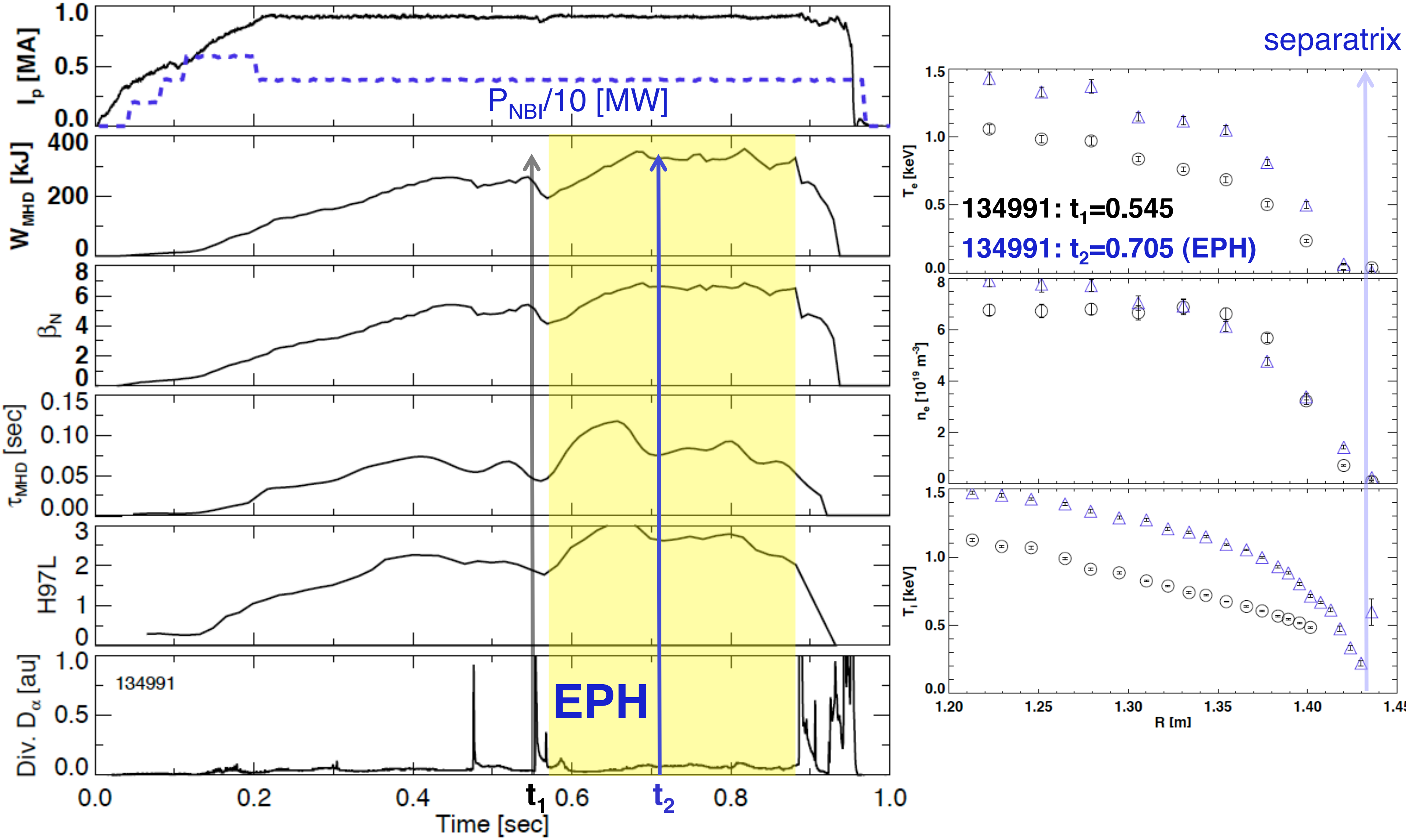




- ***Note: Pedestal $\nu_e^* \sim 0.5$-1 in H-mode***

Maingi, JNM 390-391 (2009) 440

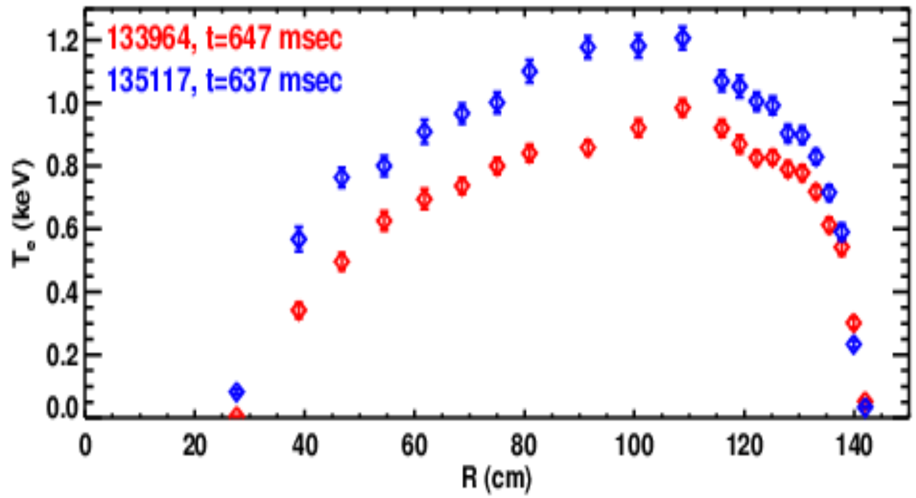
EPH-mode phase observed for several τ_E, up to ~ 300 msec

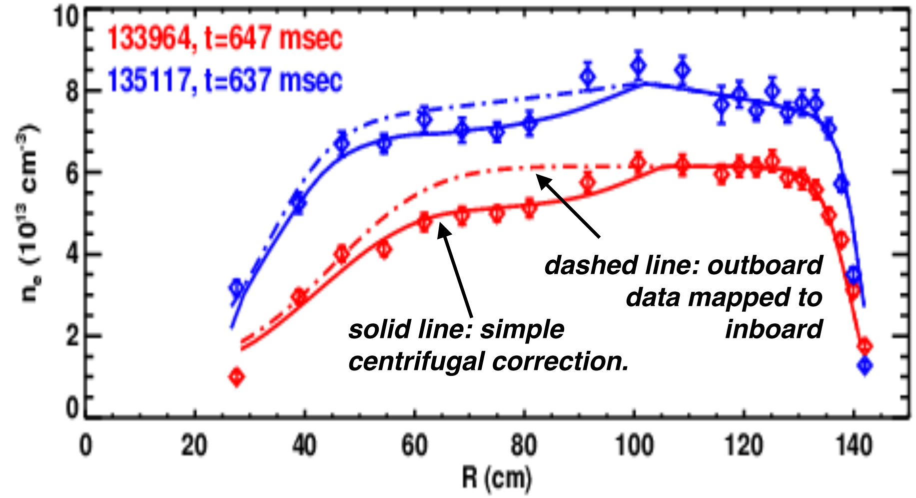


Lithium Wall Conditioning Leads to Broad Pressure Profiles Favorable For Stability

133964: High-β_P discharge, 700 kA & 0.48 T

135117: High-β_T scenario, 1100 kA & 0.44 T





Lithium conditioning leads to:

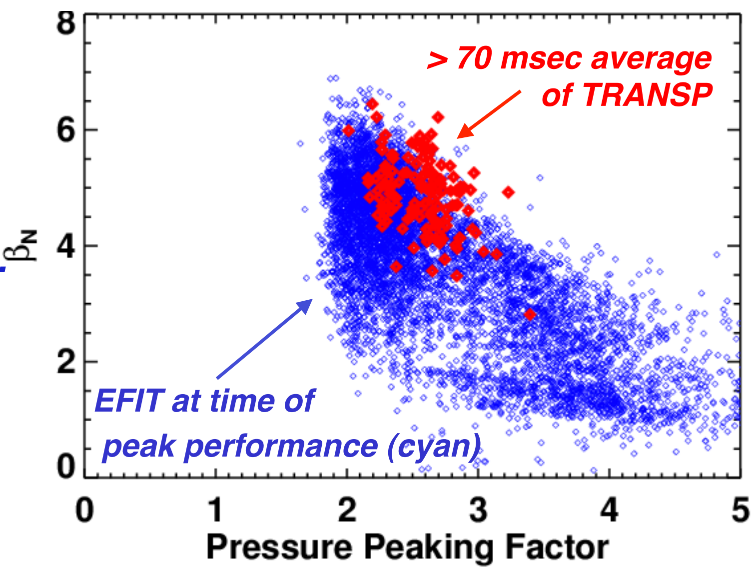
- *Inward shift of density profile.*
- *Broadening of the electron temperature profile.*

Net effect:

- *Density and temperature profiles have similar shapes.*
- *Elimination of ELMs.*
- *Broad pressure profile.*

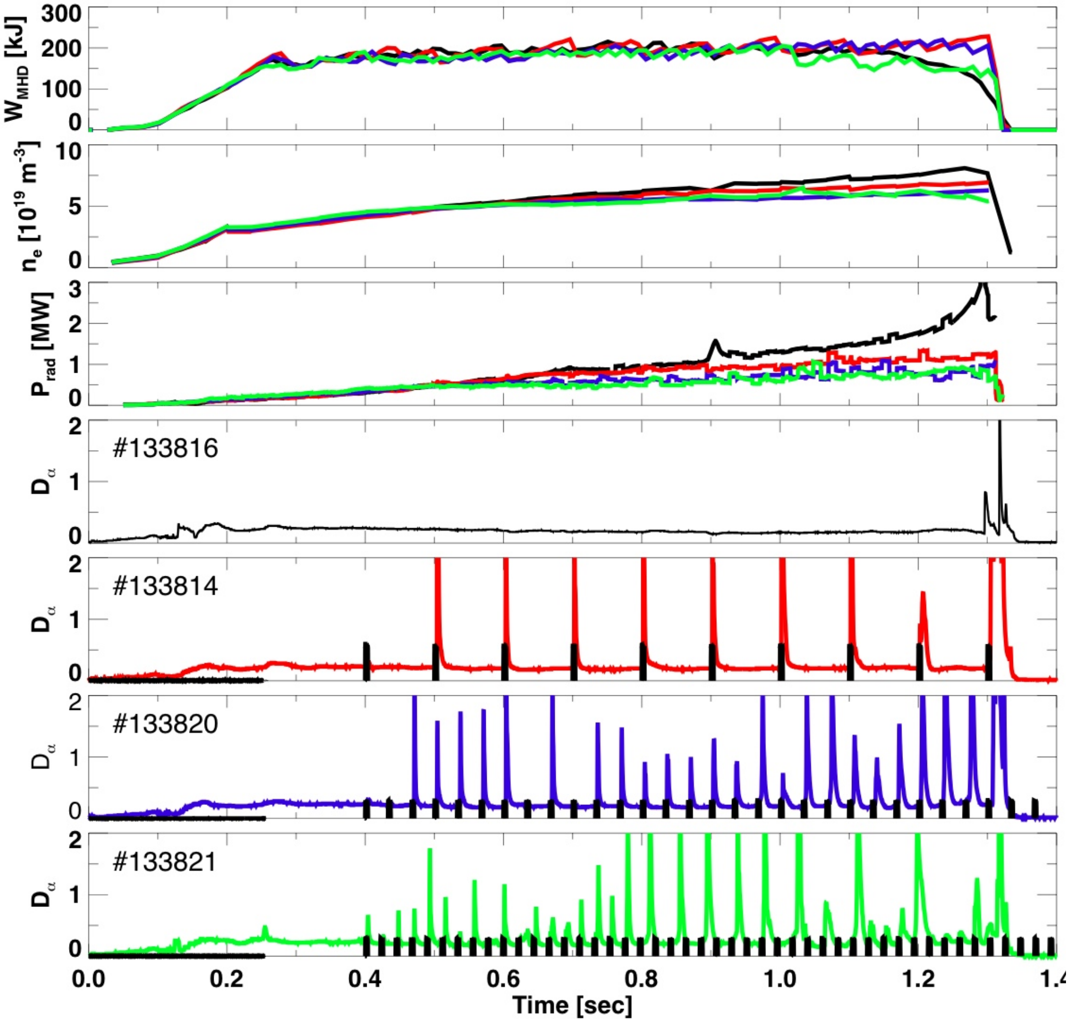
Broad pressure profile highly beneficial to ideal stability.

- *Highest β_N achieved for lowest pressure peaking factor.*

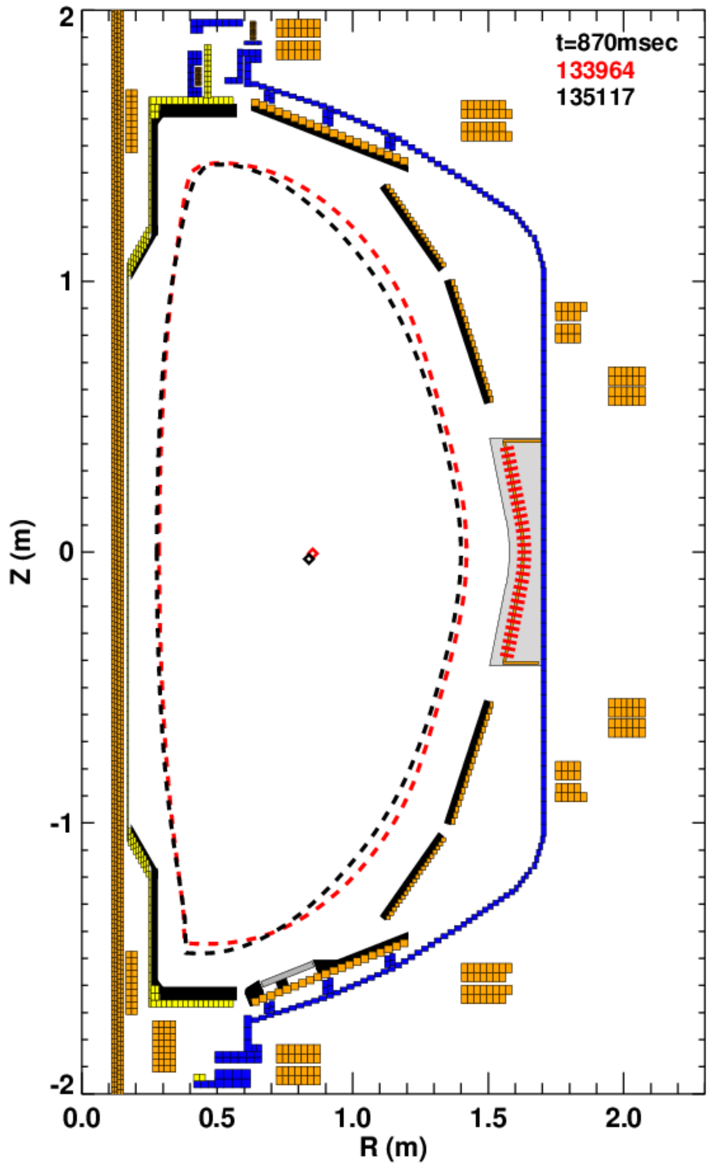


NSTX is Developing Tools To Reduce/Eliminate Impurity Accumulation in ELM-free H-modes

- Excellent particle confinement in ELM-free lithiated H-modes leads to impurity accumulation.
  - Carbon accumulation leads to fuel dilution.
  - Metals accumulation leads to large radiated power.
- Examining different methods to reduce impurity influx and confinement.
  - Divertor gas puffing.
  - Optimization of the magnetic balance.
  - Expanded lithium coverage of PFC surfaces.
  - Magnetic ELM pacing.

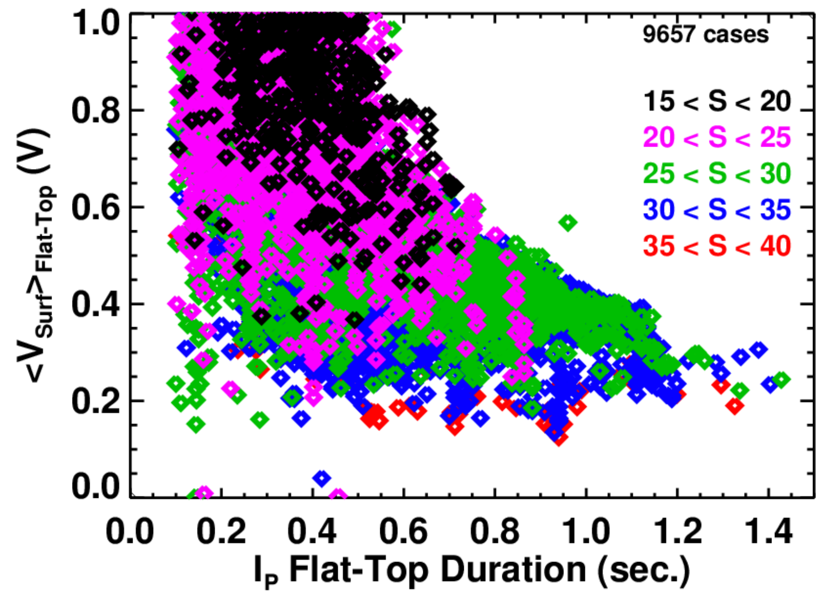


Recent Scenario Development Has Focused on Long-Pulse Development With Strong Shaping and High-β



Shape parameter S incorporates the effects of aspect ratio, elongation, and triangularity.

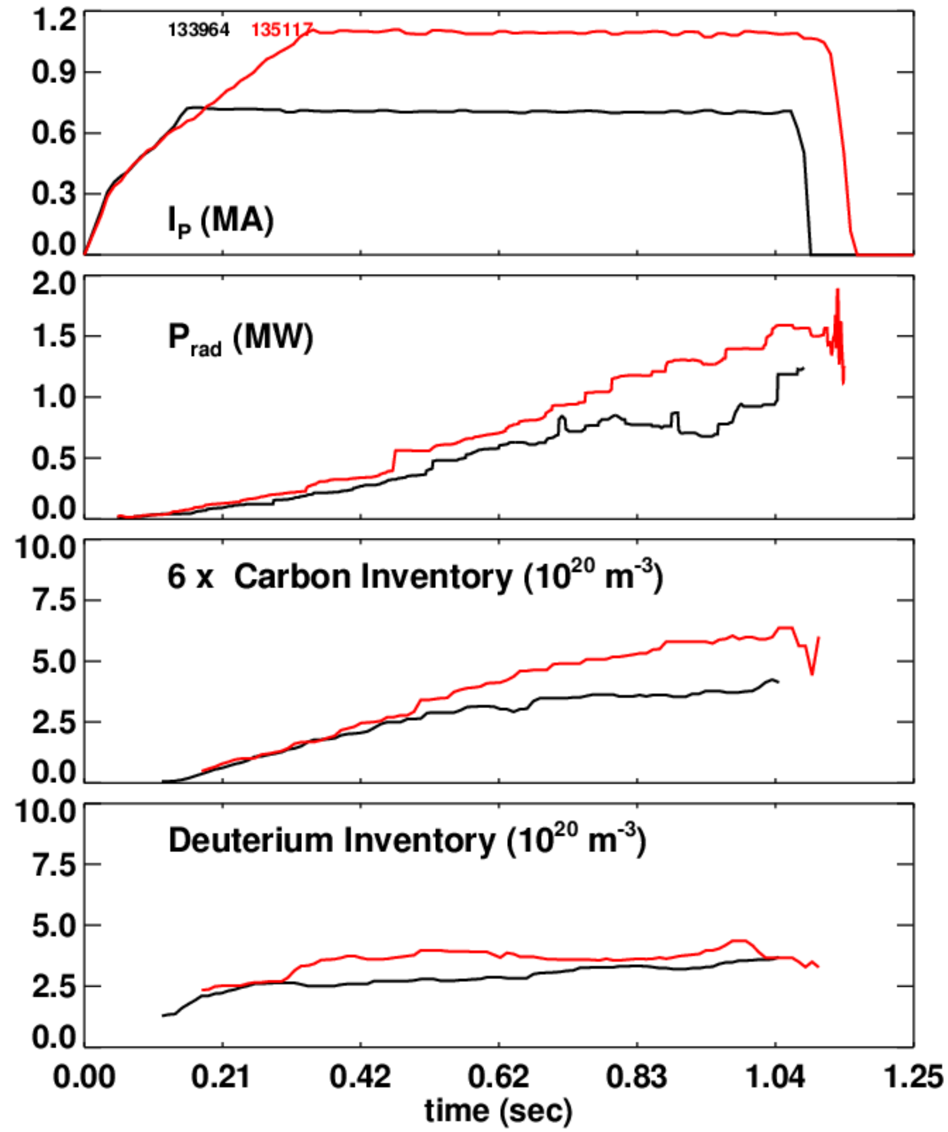
$$S = \frac{q_{95} I_P}{a B_T} \propto \varepsilon\left(1+\kappa^2\right) f\left(\kappa,\delta,\varepsilon,\ldots\right)$$



130 mV surface voltage sustained for 0.9 sec I_P flat-top with strong shaping + Li conditioning and n=1 control

ELM-Free Scenarios Have Constant Deuterium Inventory, But Suffer From Carbon and Metallic Impurity Accumulation

- Substantial peaking of the radiated power profile.
  - Implies metallic impurity accumulation in the core.
- Substantial accumulation of carbon.
- Exploration of mitigations strategies is high-priority near-term research.
  - ELM pacing
  - Snowflake divertors.
  - Divertor detachment via gas puffing.
  - RF suppression of impurity accumulation.
  - Covering of exposed stainless steel with molybdenum

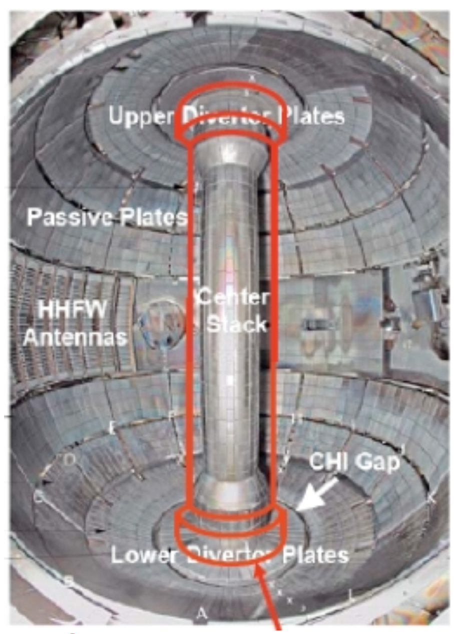


NSTX Upgrade Would Be A Major Step Along ST Development Path

(next factor of 2 increase in current, field, and power density)

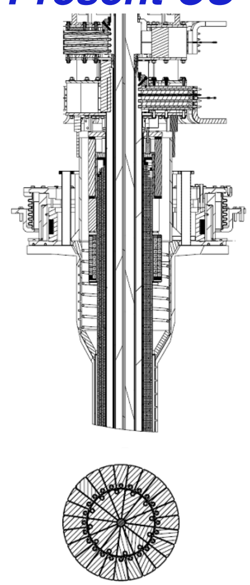
	NSTX	NSTX Upgrade	Plasma-Material Interface Facility	Fusion Nuclear Science Facility
Aspect Ratio = R_0 / a	≥ 1.3	≥ 1.5	≥ 1.7	≥ 1.5
Plasma Current (MA)	1	2	3.5	10
Toroidal Field (T)	0.5	1	2	2.5
P/R, P/S (MW/m,m^2)	10, 0.2*	20, 0.4*	40, 0.7	40-60, 0.8-1.2

*** Includes 4MW of high-harmonic fast-wave (HHFW) heating power***



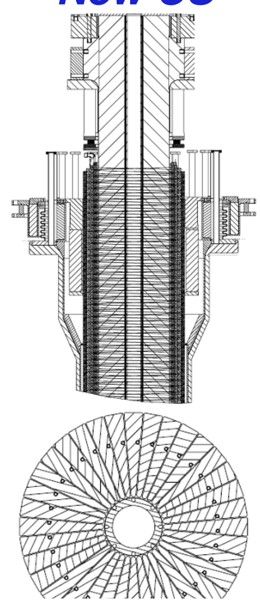
Outline of new center-stack (CS)

Present CS



TF OD = 20cm

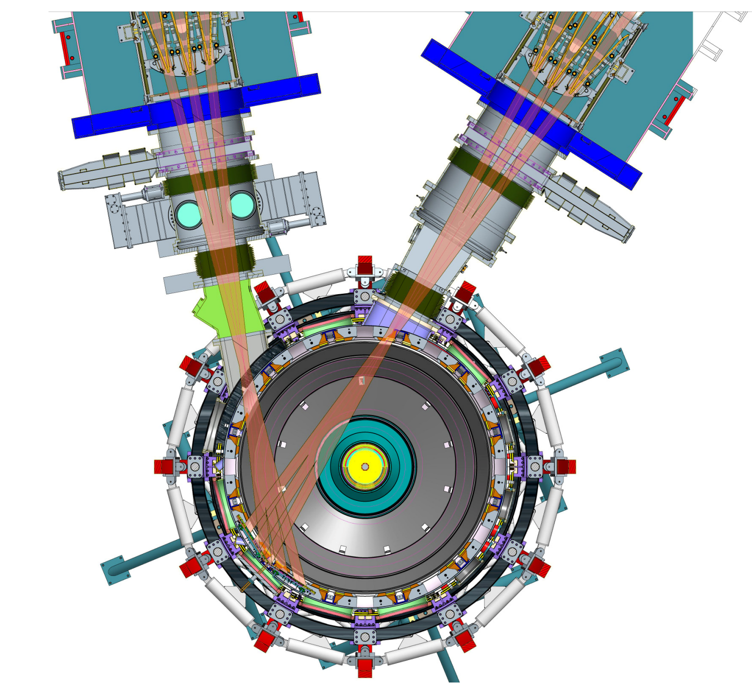
New CS



TF OD = 40cm

New 2nd NBI
(R_{TAN}=110, 120, 130cm)

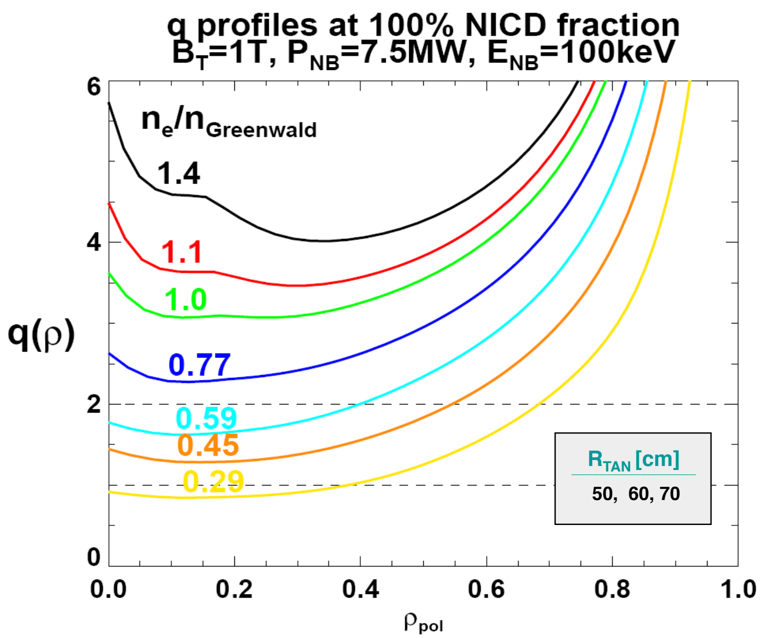
Present NBI
(R_{TAN}= 50, 60, 70cm)



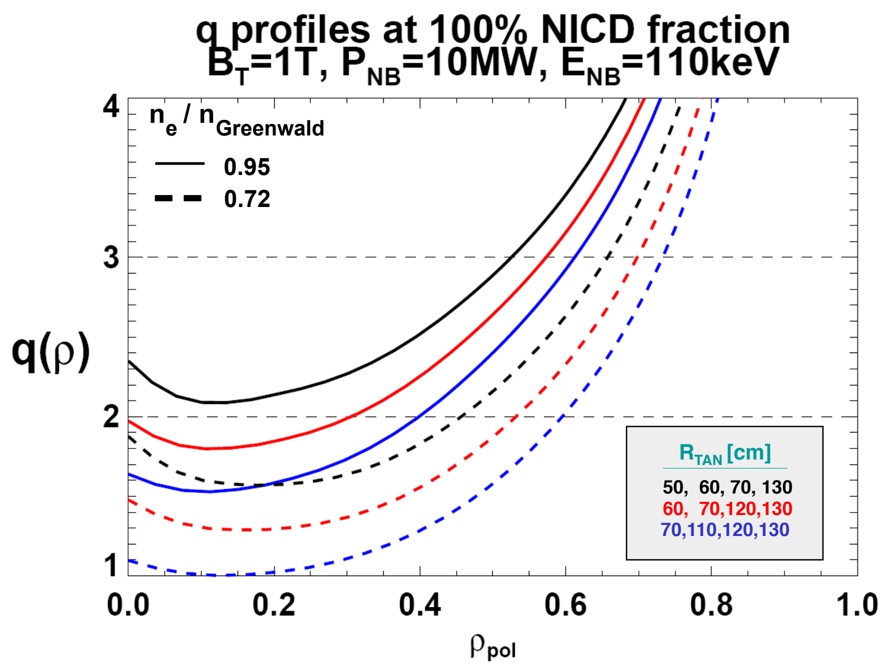
Higher Field B_T=1T from new CS + 2nd NBI Would Enable Access to Wide Range of 100% Non-Inductive Scenarios

- **New CS + present NBI-CD + fast wave:**
  - Study confinement scaling vs. I_P and B_T
    - Limited range of auxiliary power levels
  - 100% non-inductive for 1-1.5s (~1 τ_{CR})
    - NBI duration limited to 2s at 7.5MW
    - Vary q_{min} with density (CD efficiency $\propto T_e/n_e$)

- **Addition of 2nd NBI would enable:**
  - Study confinement scaling vs. I_P and B_T with:
    - Full range of auxiliary power available
    - Assured access to high-β at reduced ν*
  - 100% non-inductive for 3-4 τ_{CR} → relaxed J(r)
    - 10MW NBI available for 5s
    - Control q_{min} & q-shear w/ NBI source, n_e, & B_T
    - Study long-pulse NTM stability with q > 2
  - Study compatibility of high-β w/ PMI solutions



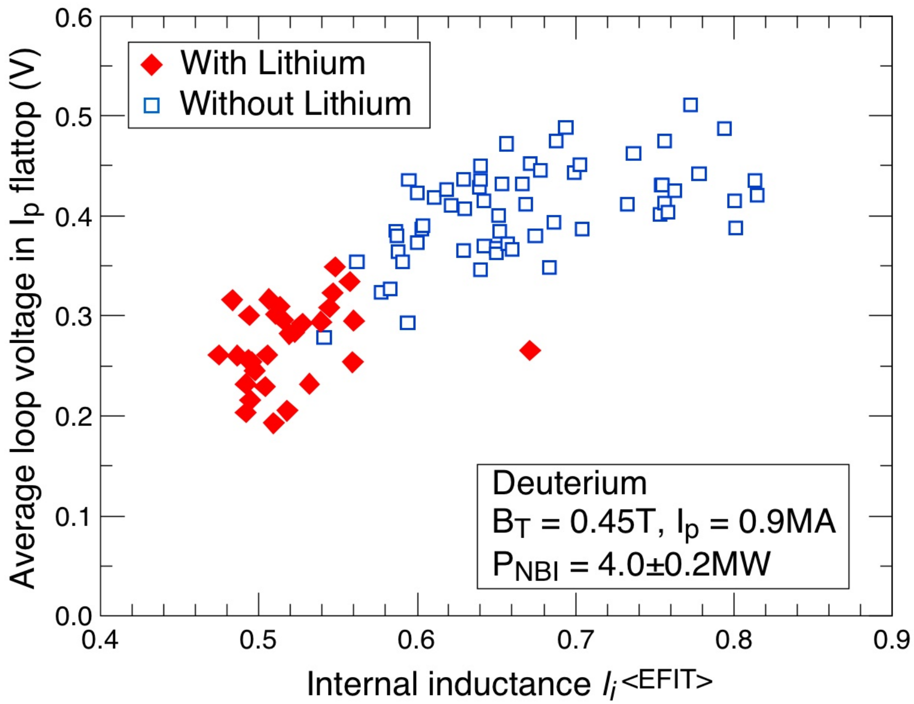
I_P = 0.8-1.2MA, H_{98y2} = 1.2-1.4, β_N = 4.5-5, β_T = 10-12%, 4MW RF

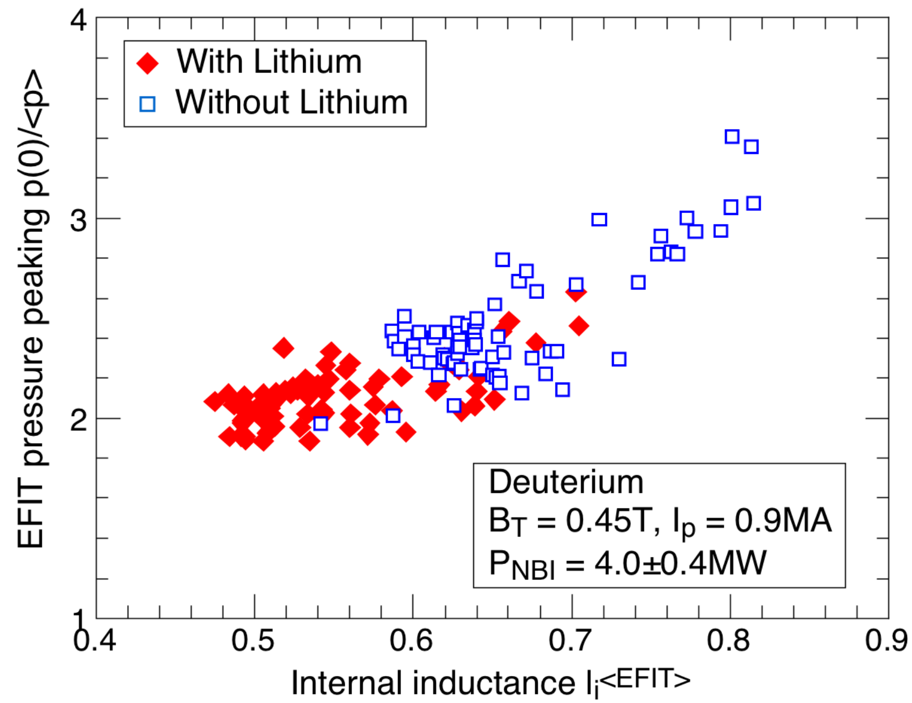


I_P = 0.95MA, H_{98y2} = 1.2, β_N = 5, β_T = 10%, 4MW RF

Broader T_e Profile with Lithium Coating Reduces Both Inductive and Resistive Flux Consumption

- Critical issue for development of low-aspect ratio tokamaks
  - Little space for conventional central solenoid providing inductive current drive

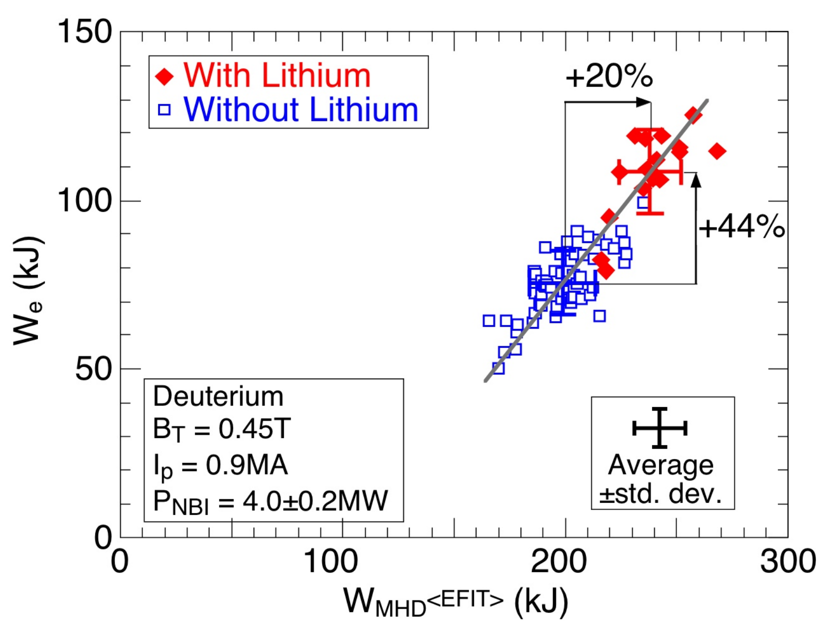




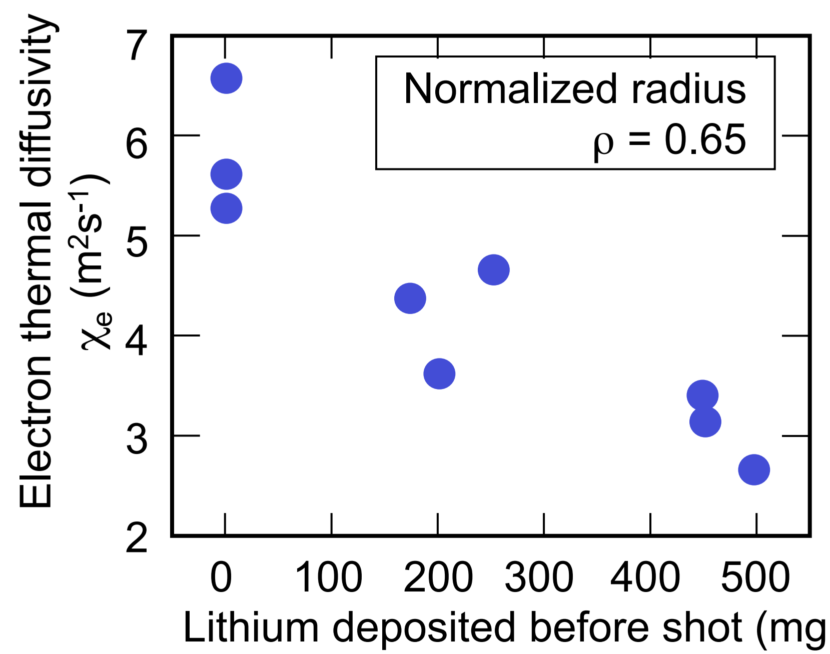
- Reduction occurs despite increase in $\langle Z_{eff} \rangle$ in ELM-free H-modes after lithium coating

Confinement Improves, and Temperature Profiles Broaden, With Li Conditioning of the PFCs

Both Total and Electron Stored Energy Increase with Lithium Conditioning[1]

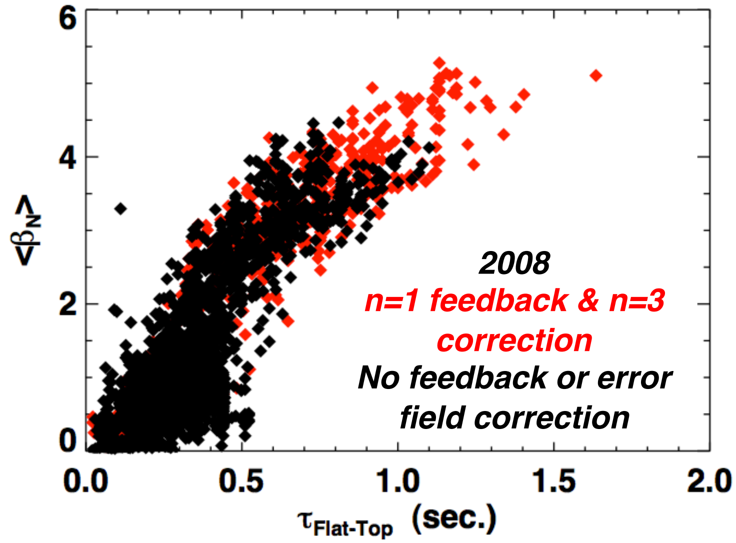


Increased Lithium Deposition Reduces Transport[2]

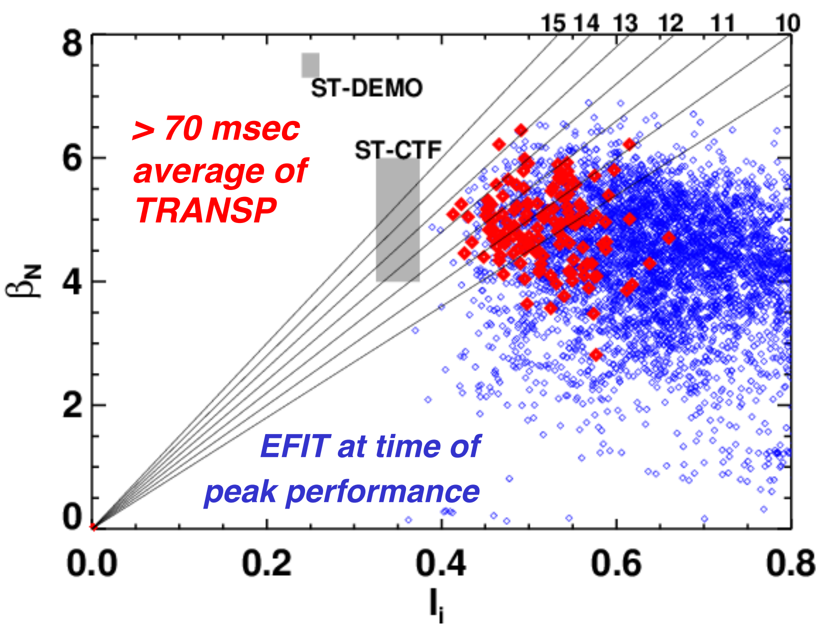


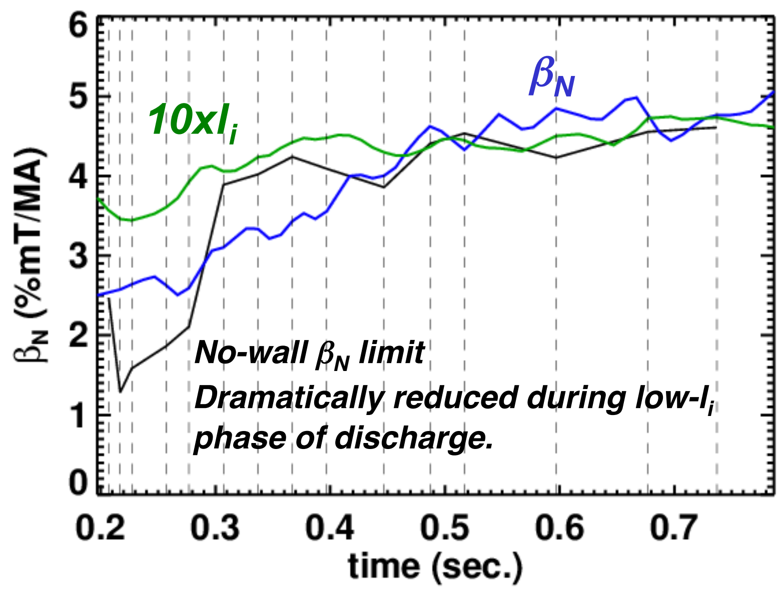
- Electron stored energy increase due to a broadening of the profiles.
- TRANSP analysis shows reduced transport in the outer part of the plasma as lithium deposition is increased.
- Root cause of confinement improvement with lithium is not understood.
  - Ions remain approximately neoclassical.
  - Electron transport in NB-heated H-mode ST plasmas is not understood.

NSTX Uses Active Mode Control to Access High β_N Regimes



- *MHD control with 3-D fields facilitates long pulse high-β operation.*
  - *Dynamic correction of n=1 error fields*
  - *Fast RWM control.*
  - *Pre-programmed n=3 correction*
- *β_N/l_i ratios approaching those needed for next-step devices*
- *Ideal stability calculations show reduced β_N limit in lowest-l_i targets.*



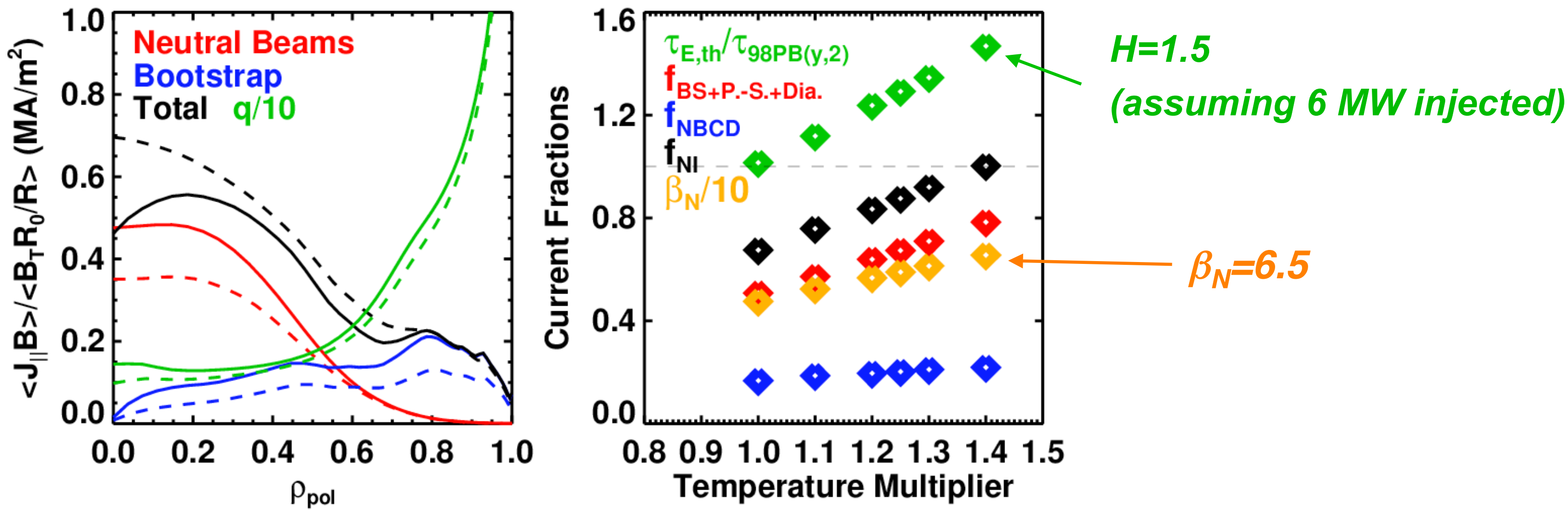


Fully Non-Inductive Operations Possible with Higher Temperature, Same Density

- TRANSP simulations with boundary and profile shapes from high-κ, high-β_P discharge 133964, Z_{eff}=3
- Scale T_e and T_i by the same factor, leaving densities unchanged.

Solid: Scaled Profiles for f_{NI}=1

Dashed: Reference Profiles



- With Z_{eff}=2, required temperature increase is only 25%.